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## Rotorcraft TCAS Evaluation Group 3 Results

Albert J. Rehmann

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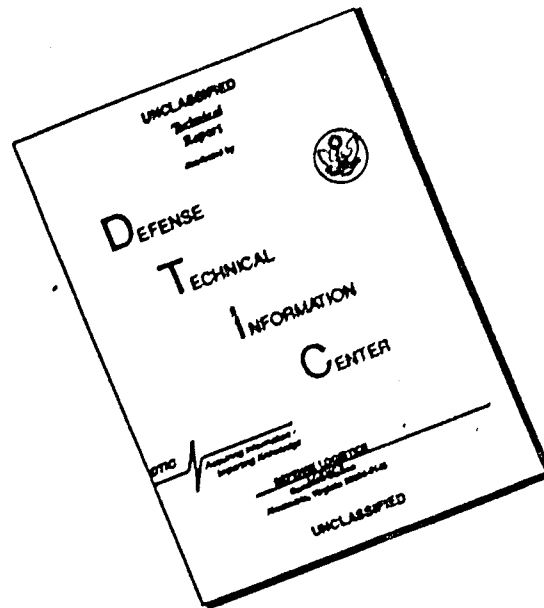
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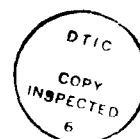
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16. Abstract <p>This report documents the operational flight test of a prototype Traffic Alert and Collision Avoidance System (TCAS) installed in a Sikorsky S-76 helicopter. The prototype TCAS, programmed to encompass the functions of a TCAS I, was flown to five east coast terminal cities, and operated along defined helicopter routes therein. The test results validated the minimum proposed TCAS I configuration. Further results recommend enhancements, to be included as options to improve the usefulness of TCAS I.</p> <p>Keywords:</p>			
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## EXECUTIVE SUMMARY

This report documents Group 3 results of the Federal Aviation Administration (FAA) Technical Center's helicopter Traffic Alert and Collision Avoidance System (TCAS) evaluation. In this group of tests, a TCAS I equipped Sikorsky S-76 was flown along helicopter routes in Atlantic City, Philadelphia, New York, Boston, and Washington, D.C. Surveillance data were gathered and processed to validate the proposed Radio Technical Commission for Aeronautics (RTCA) Minimum Operational Performance Specification (MOPS) of transmitter power and whisper shout power programming.

After each flight, interviews with Technical Center project pilots were conducted to gather pilot factors data. FAA pilot opinion was compared to a census of commercial pilot responses on the subject of helicopter safety. The two groups of responses produced similar conclusions; the main one being that added workload can be a detraction from flight safety. FAA pilots stated that excessive TCAS alerts could create a distraction causing added workload.

As a result of FAA pilot comments, special attention was given to validating a traffic advisory logic for helicopter operation. Tau and modified distance (DMOD) threat screening were adapted from TCAS II and optimized for the slower speeds associated with helicopters. A feature of the logic is that enhanced protection against high speed intruders is offered. False and nuisance alerts due to multipath and on-ground aircraft are addressed. This report recommends providing optional provisions to sense radar altitude.

Alert rates with the optimized TCAS I logic are 3 or 4 per hour compared to 15 to 20 per hour with the TCAS II logic (version 9.0) programmed into the TCAS Experimental Unit (TEU).

## 1. INTRODUCTION.

### 1.1 PURPOSE.

This report documents the results of the third group of tests of a Traffic Alert and Collision Avoidance System (TCAS) unit installed in Sikorsky S-76.

### 1.2 BACKGROUND.

A test plan (reference 1) has been developed by ACT-140 which outlines three major groups of tests to be conducted. Group 1 tests were designed to verify the TCAS Experimental Unit (TEU) installation and operation in the aircraft (reference 2). Group 2 tests were designed to evaluate antenna performance and surveillance link reliability in controlled tests with Technical Center chase aircraft (reference 3). Group 3 work, documented in this report, was designed to examine the performance of a prototype TCAS installed in a S-76 operating along defined helicopter routes into and around several east coast cities, including Philadelphia, Boston, New York, Newark, and Washington, D.C.

### 1.3 SCOPE.

The analysis defined in this report is limited to the examination and presentation of Group 3 flight data to either validate current TCAS I concepts, or to demonstrate improvement in those areas which are deficient. Specifically, this analysis is limited to the topics of surveillance (section 5), traffic advisory generation (section 6), and signal corruption by multipath (section 7).

### 1.4 EQUIPMENT DESCRIPTION.

A TEU was built at the Massachusetts Institute of Technology (MIT) Lincoln Laboratory and was designed to be reconfigurable in order to emulate several TCAS specifications.

In the Technical Center flights the TEU was configured to encompass the functions of a TCAS I as defined in a draft Minimum Operational Performance Specification (MOPS) (reference 4). The draft MOPS defines a very basic TCAS I as a minimum, and also lists numerous enhancements to improve TCAS I performance.

The MOPS also permits a TCAS I operating mode whereby TCAS I interrogations can be as high in peak power as TCAS II interrogations, with the condition that TCAS I must have the capability to transmit Mode S broadcast signals.

The TEU interrogation sequence was programmed to emulate the TCAS I operating mode.

Table 1 lists the operating characteristics of the Lincoln Lab TEU and compares them to the appropriate current draft MOPS requirement.

The display in the S-76 was essentially a TCAS II display with the resolution advisories inhibited. The TCAS II functions of shared weather presentation and selectable 15-second display of traffic (all prox switch) were retained.

TABLE 1. TEU CONFIGURATION IN FAA FLIGHT TEST

TCAS I Characteristic	MOPS Reference Paragraph	Minimum Required	System Enhancement	TEU Operating Capability In FAA Flight Test
Range Accuracy = $\pm 0.1$ nmi	1.5.1 b	*		Range Accuracy = $\pm 0.01$ nmi
Bearing Accuracy = $\pm 45^\circ$	1.5.1 c	*		Bearing Accuracy = $\pm 8^\circ$ RMS
Surveillance Range = 4 nmi	1.5.1 c	*		Surveillance Range = 6.2 nmi; Mode C and Non-Mode C Tracking is Performed
False Track Reduction	1.5.1 d	*		TEU Uses TCAS II False Track Rejection Logic
Own Altitude Digitizing	1.5.2.2 a		*	TEU Senses own Aircraft Mode C
Improved Bearing Accuracy (No Specification)	1.5.2.2 b		*	Bearing Accuracy = $\pm 8^\circ$ RMS
Declutter the Display	1.5.2.2 c		*	TEU Uses TCAS II TA Logic (this paragraph refers specifically to altitude discrimination of threats)
Use of TAU to Prioritize Intruders	1.5.2.2 d		*	TEU uses TCAS II TA logic: $\tau = 35$ sec, DMOD = 0.4 nmi
Added Mode S Capability	1.5.2.2 e		*	TEU has Mode S
Density Requirement = 0.0M Aircraft/Sq nmi	1.6	*		TEU uses TCAS II whisper shout sequence; demonstrated in 0.12 Ac/Sq nmi density
Receiver Sensitivity = -73 $\pm 3$ dBm	2.2.1	*		TEU MTL = -76 dBm
Transmitter Output = 50 dBm minimum, 54 dBm maximum	2.2.2	*		TEU transmitter output = 56.3 dBm (unattenuated)
Interrogation Spectrum	2.2.2.2	*		TEU meets requirements
Mode C Reply Reception	2.2.1	*		TEU meets requirements
Reduction of Synchro noise, Garble	2.2.2		*	TEU uses fine (nine level) whisper shout sequence; also uses three degarblers
Interference Limiter	2.2	*		Not coded in TEU (performed in post-flight processing)

## 1.5 POST-FLIGHT DATA PROCESSING.

TCAS data recorded during each flight consisted of own aircraft data, target aircraft reply data, and target aircraft track data.

Aircraft position information was determined from the NIKE/Hercules radars, the laser tracker, or the extended area instrumentation radar (EAIR). Data from these trackers were time tagged to permit merging with flight data.

The first step in the Center's data processing cycle was the creation of a data base for each flight. The data base contained own aircraft data and target track data taken directly from the flight data tapes and aircraft position data from one or more of the precision ground trackers. Before the intruder reply data were entered into the data base however, it was correlated with the intruder track data. The correlation matched raw replies (in the reply buffer) with aircraft tracks (in the track buffer), according to the track extension parameters defined in the TCAS I MOPS. Thus, this procedure is a reverse order tracker wherein real aircraft replies are distinguished from fruit and are further matched to a particular aircraft track. Using this technique, surveillance parameters, including update rates versus interrogator power, update rates versus range, and multipath elimination, are examined through the use of the data base.

Intruder track data and own aircraft data taken from the data base were played back through a TCAS logic model resident on the Center's Honeywell computer. This technique permits the optimization of Traffic Advisory (TA) generation criteria through an analysis where TA rates were compared versus differing TA thresholds.

## 2. TEST DESCRIPTION.

The TCAS equipped S-76 was flown along commercial helicopter routes in five east coast cities. Maps of these cities are shown in figures 1 through 4. The maps show the local traffic control area (TCA), the ground track flown by the S-76 landmarks used as position fixes, and time tags to identify specific events which occurred during the flight.

Figure 1 shows operations in the Philadelphia area, figure 2 shows the New York and Newark area, figure 3 shows the Boston area, and figure 4 shows the Washington area operations.

---

Two studies have been published which examine the hazards of helicopter operations. Reference 5 is a compilation of accident data from the National Transportation Safety Board (NTSB) reports and briefs, along with interviews with the operators and pilots actually involved in the incidents. Reference 6 is a user survey which contains helicopter operator and pilot responses to questions specifically related to midair and near midair collisions (NMAC's).

In reviewing references 5 and 6, TCAS personnel were attempting to:

- a. Understand the factors associated with near NMAC's. This information was used in selecting the questions asked of the pilots in the post-flight debriefing (section 3.1).

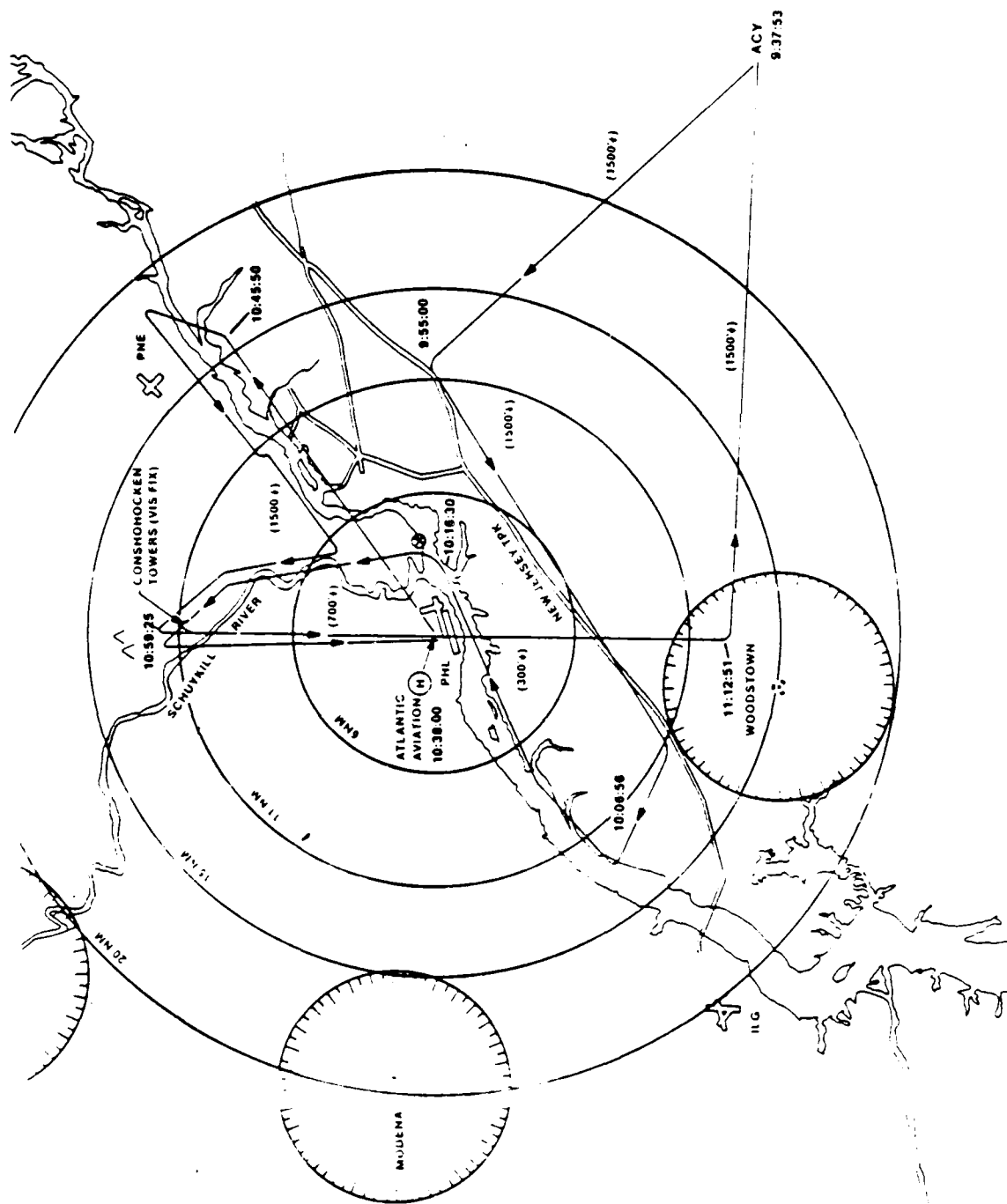


FIGURE 1. PHILADELPHIA AREA TCA

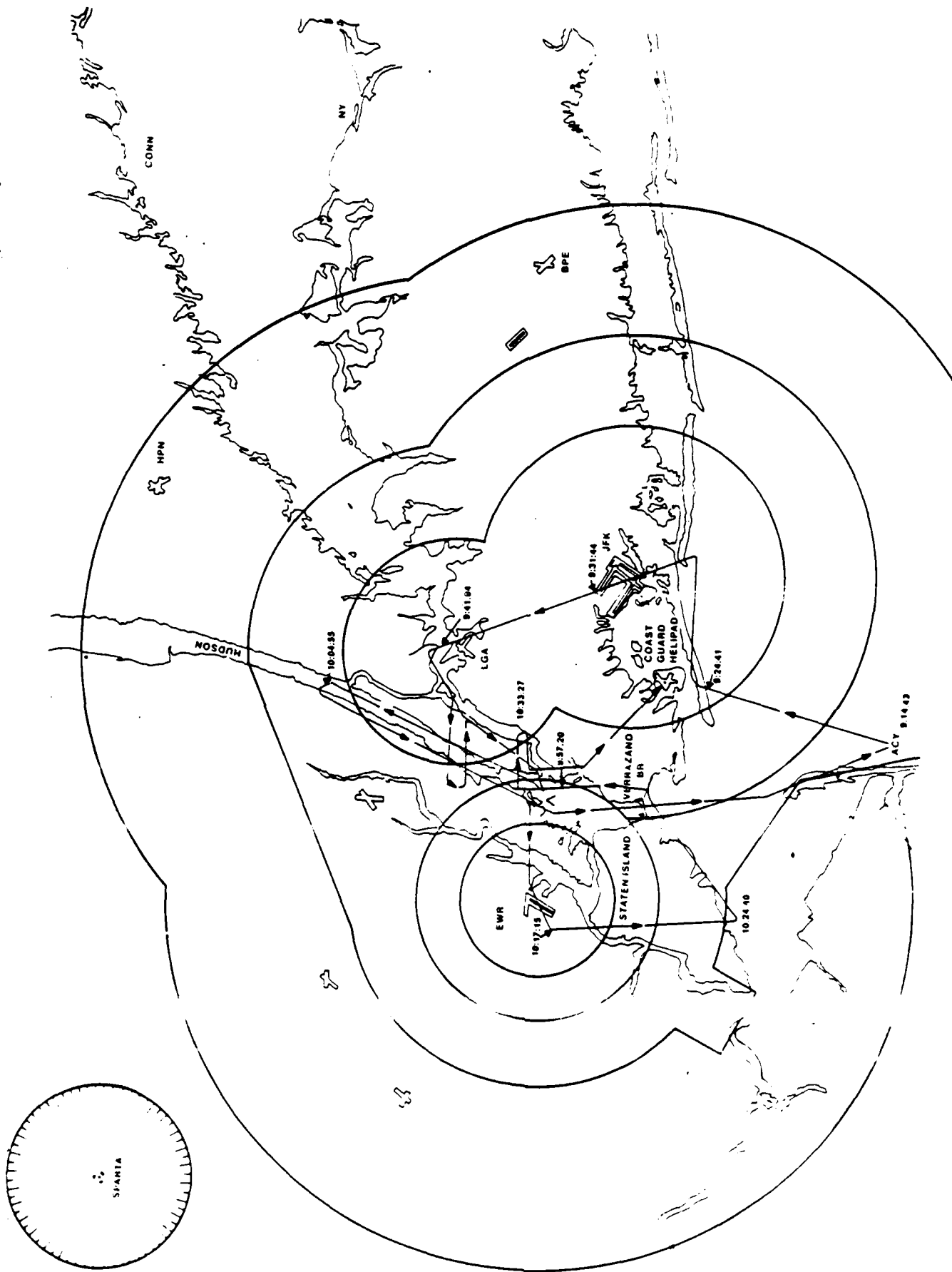


FIGURE 2. NEW YORK AREA ICA

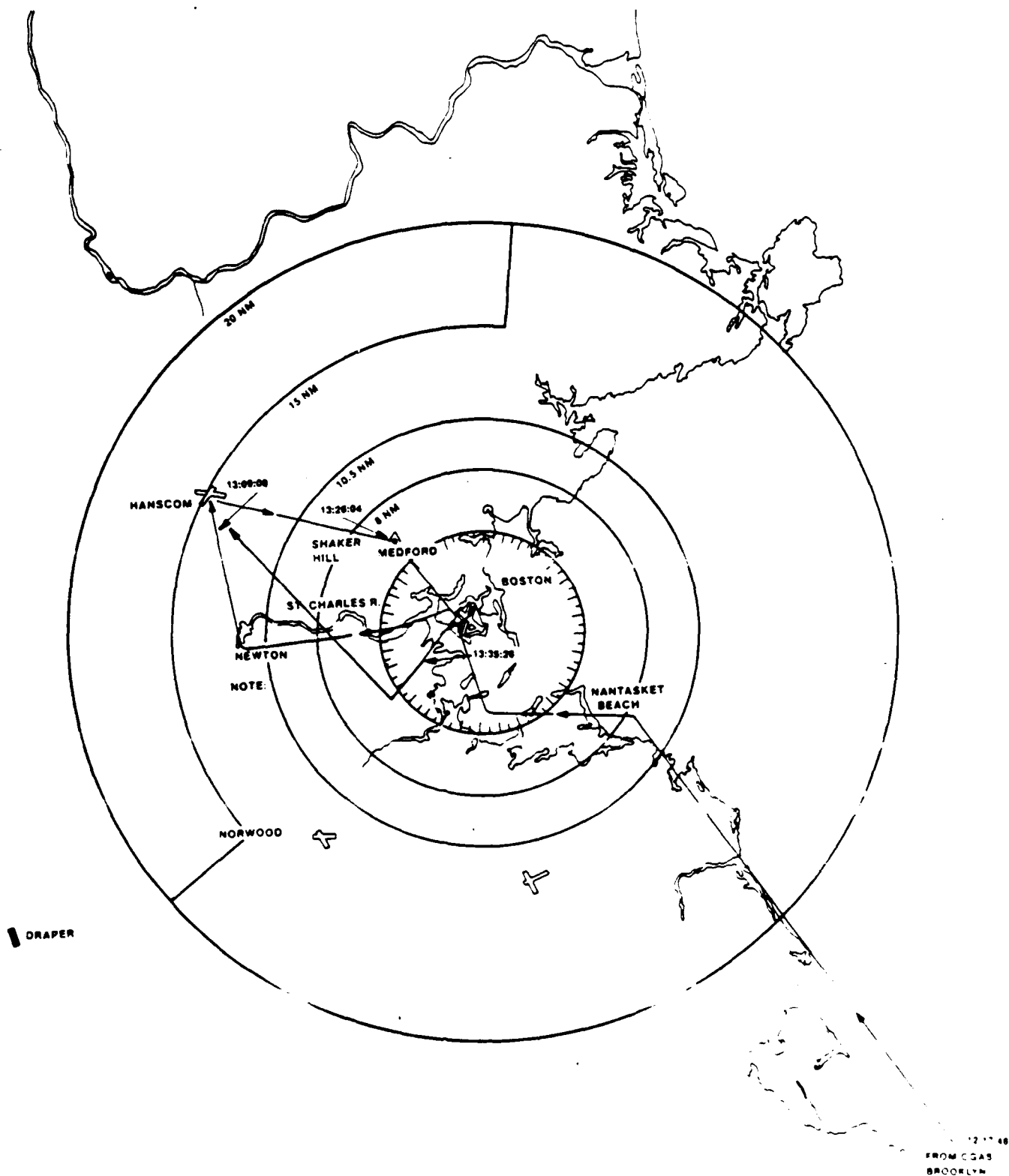


FIGURE 3. BOSTON AREA TCA

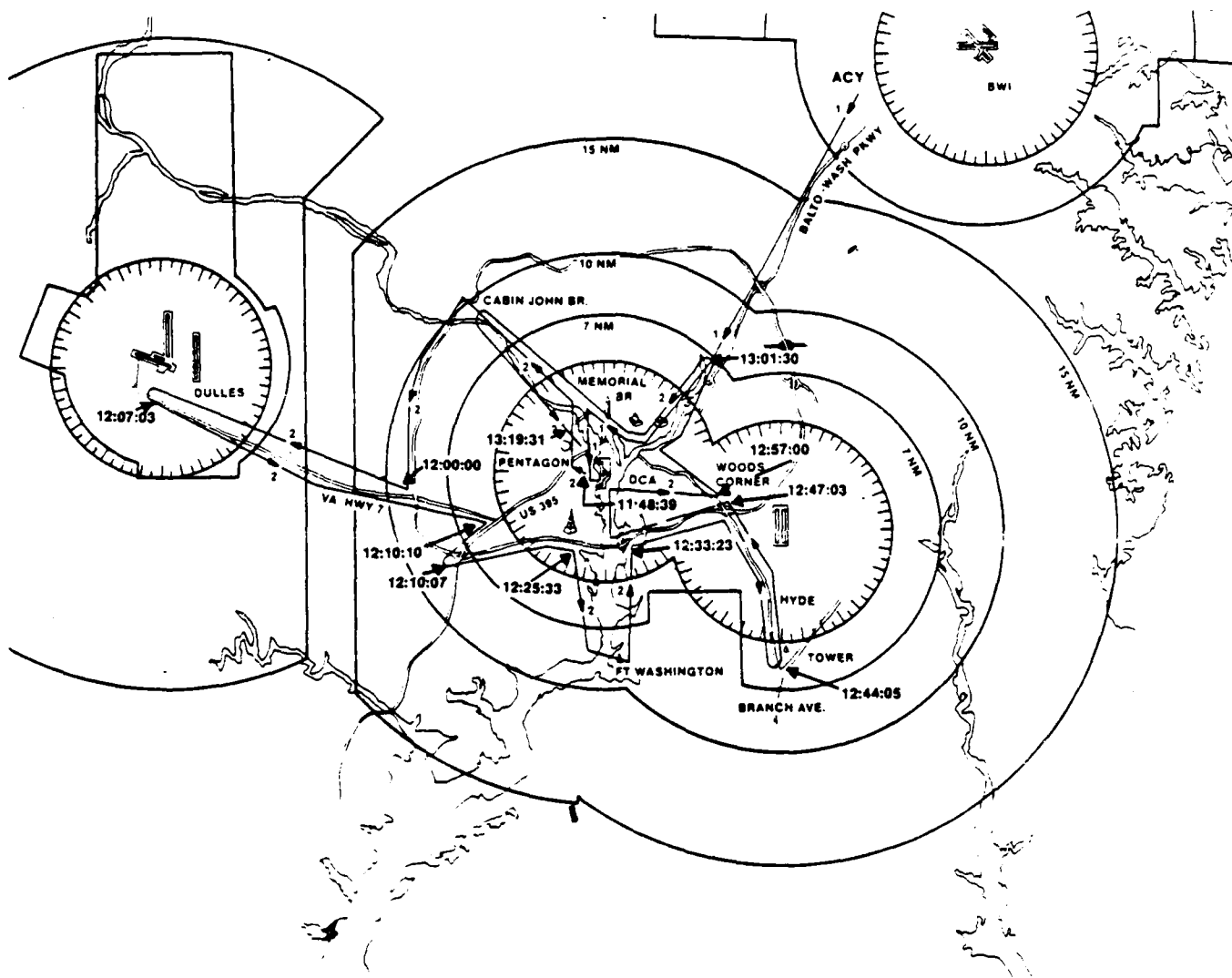


FIGURE 4. WASHINGTON AREA TCA



b. Gauge the correlation of FAA test pilot responses with commercial pilot (and operator) opinion. The FAA test pilot responses were used to determine how adequately the helicopter TCAS, as implemented in the S-76, will be able to meet the needs of helicopter operators and pilots at large.

The key items gleaned from the literature review are:

a. Single Pilot Versus Dual Pilot Operation. Seventeen mission types were reviewed for one or two pilot cockpits. Of these, 53.2 percent of total helicopter utilization involves strictly two pilot crews.

b. Root Cause of Helicopter Accidents. In all pilot-caused accidents, inadequate training and/or proficiency was the leading cause. The second leading cause of accidents is pilot fatigue due to excessive workload.

c. Flight Profiles. Helicopter pilots tend to fly low to avoid interaction with air traffic control (ATC), to stay clear of fixed wing aircraft, and to facilitate landing in case of machine failure.

d. Incidence of NMAC. NMAC's were most frequently reported as occurring in straight and level flight on approaches or departures in terminal areas.

e. Critical Quadrant. Helicopter pilots feel most susceptible to collisions from the left rear.

f. ATC Involvement. The consensus among commercial pilots and operators is that ATC has had little involvement in NMAC.

g. Pilot Perceived NMAC Risk. Commercial pilots and operators have ranked the NMAC risk equal to pilot fatigue and machine failure. Moreover, the consensus data made six recommendations for present and future changes to improve the safety of helicopter operations. One of the proposed improvements was the installation of a reliable collision avoidance system.

### 3.1 PILOT SURVEY QUESTIONS.

After each flight, TCAS project personnel (including flight crew and project coordinators) conducted an interview with the Technical Center test pilots who flew the mission. During the interview, the TCAS project manager asked the pilots to comment on their experience with helicopter TCAS according to the following set of questions:

a. What is your previous experience (in-flight hours) with TCAS?

b. Did you find TCAS (a) Useful? (b) Timely? (c) Necessary? or (d) Correct?

c. Was TCAS ever helpful in maintaining separation?

d. Did TCAS increase/decrease workload?

e. How, in your opinion, did TCAS operate (i.e., bearing quality/track reliability)?

f. Would you/how would you change the TCAS displays, controls, specified procedures?

g. Did TCAS augment/conflict with ATC?

h. General comments, observations, suggestions.

Only Technical Center test pilots participated in this test program; no industry pilots participated.

### 3.2 FAA TEST PILOT RESPONSES.

#### 3.2.1 Pilot Experience.

Six Technical Center test pilots flew the missions to the east coast cities. Their experience in the S-76 ranges from recently certified to many hours in the machine. Similarly, their prior experience with TCAS ranges from none to several hours flying prototype systems. The experience of each pilot is described in table 2.

TABLE 2. FAA PILOT EXPERIENCE IN S-76 AND TCAS

<u>FAA Pilot</u>	<u>Hours in S-76</u>	<u>Hours with TCAS</u>
1	150	40
2	30	1
3	150	10
4	500	150
5	70	7
6	50	50

#### 3.2.2 Questionnaire Responses.

Table 3 contains the responses to the questions in section 3.1. Some questions are answered with "yes" or "no" responses followed by notes. The notes are additional comments made by the pilots to either emphasize or qualify their responses, and are described in the table.

Additional pilot comments are as follows:

a. "When en route, TCAS is pretty good; not many false TA's and bearing not too bad."

b. "Multipath and on-ground targets are overwhelming."

c. "En route, TCAS is invaluable."

TABLE 3. FAA PILOT QUESTIONNAIRE RESPONSES

Question	Pilot 1		Pilot 2		Pilot 3		Pilot 4		Pilot 5		Pilot 6	
	<u>Yes</u>	<u>No</u>	<u>Yes</u>	<u>No</u>	<u>Yes</u>	<u>No</u>	<u>Yes</u>	<u>No</u>	<u>Yes</u>	<u>No</u>	<u>Yes</u>	<u>No</u>
1. Pilot experience (see table 1)												
2. Was TCAS:												
Useful	x		x		x		x		x		x	
Timely	x		x		x		x		x		x	
Necessary	x		x		x(Note 2)		x		x		x	
Correct	x			x	x			x(Note 5)	x		x	
3. Was TCAS helpful in maintenance separation	x		x		x		x		x			
4. TCAS increase/decrease workload												
Increase Slightly												
About Same												
Decrease												
Increase (Note 6)												
About Same (Note 8)												
5. TCAS operate properly		x(Note 1)	x		x		x		x		x	
6. Would you change displays/controls		x		x	x(Note 3)		x			x		
7. Did TCAS agree with ATC		x	x		x(Note 4)		x		x		x	
8. General comments, suggestions												
TOTALS BY PILOT	5	3	6	2	8	0	7	1	7	1	7	1

TABLE 3. FAA PILOT QUESTIONNAIRE RESPONSES (CONTINUED)

Note 1. Question 5, pilot 1; "Did TCAS operate properly?". This "no" response was the result of a consistent bearing error observed by the pilot. This pilot also commented in question 7, that TCAS did not agree with ATC, also based on the bearing error. After the flight, it was determined that the cause of the bearing error was an improper setting of the top antenna bias word.

Note 2. Pilot 3, question 2; "Was TCAS helpful in maintaining separation?". This pilot stated that TCAS was "absolutely essential" when flying en route. He also commented that TCAS was necessary when flying in terminal areas.

Note 3. Pilot 3, question 6; "Would you change displays/controls?". This pilot stated that a continuous traffic display would be desirable compared to the 15-second time out of the "all-prox" function, when flying in terminal areas.

Note 4. Pilot 3, question 7; "Did TCAS agree with ATC?". Pilot 3 was favorably impressed when a coalatitude target of opportunity (TOP) overtook the S-76. As the incident unfolded, the TCAS presentation augmented ATC's traffic advisories such that the pilot relied on TCAS to resolve the conflict. The actual response to this question was "yes +". This incident is further described in section 3.2.3.3.

Note 5. Pilot 4, question 2; "Was TCAS correct?". The "no" response is the result of display saturation over Washington National Airport. When flying the river approach, heavy traffic plus multipath filled the traffic advisory display with targets. This pilot called this condition "overwhelming," and stated it increased workload by creating distractions when no real threat was present.

Note 6. Pilot 4, question 4 (see note 5 above).

Note 7. Pilot 4, question 5; "Did TCAS operate properly?". This pilot observed an apparent hole in the antenna coverage when a TOP overtook the S-76. The TOP approached from 6 o'clock and approximately 500 feet higher in altitude than the S-76. The aircraft had a slight rate of descent. No traffic advisory was issued by TCAS until the intruder was nearly overhead.

Note 8. Pilot 4, question 6; "Would you change displays/controls?". This pilot stated that TCAS "increased" workload when he recalled an incident where he mistook a false multipath track on the display for a second aircraft visible in the general direction.

d. "False tracks are very distracting; the pilot is better off without a display. The activity distracts a pilot from flying."

e. "In single pilot operation, the pilot can get very busy. Audio prompt is mandatory. Should be a low tone in headphones. False tracks can also be a serious distraction."

f. "I liked the display presentation very much; not much useless information."

g. "At first I wanted to know where everyone was all the time. Later on, the blank scope was ok and I could get traffic when I wanted."

### 3.2.3 Incidents With Targets of Opportunity.

3.2.3.1 Mission 101885, Philadelphia Area. At 10:41:40 (figure 1) a traffic advisory was generated against a coalitude intruder. A few seconds later, a second advisory was generated on an intruder 400 feet low. The pilot in command visually acquired both targets; a Bell 206 (coalitude) and a Hughes 500 (400 feet lower). Both helicopters were opposite direction traffic. The Bell 206 passed 0.2 nautical miles (nmi) to the right and the Hughes 500 passed directly below.

After the incident, the pilot commented that TCAS augmented visual acquisition. He also stated that he turned to avoid the coalitude aircraft.

3.2.3.2 Mission 121185B, Washington, D.C., Area. At 13:19:31 (figure 4) the S-76 encountered a coalitude helicopter crossing from left to right. The pilot visually acquired the intruder, a helicopter of unidentified type, several seconds before TCAS issued a TA. The intruder eventually passed approximately 0.25 nmi behind the S-76.

After the incident, the pilot commented that the visual scene agreed with the TCAS presentation and that he did turn slightly to increase separation with the intruder aircraft. It was the pilot's estimation that this incident may have been an NMAC if no avoidance maneuver was made.

3.2.3.3 Mission 121985A, New York Area. At 10:02:15, over the Hudson River, ATC called traffic (a light twin); same direction, coalitude. Almost coincidentally, TCAS generated a traffic advisory. The display presentation showed the intruder slightly above and to the left of the S-76. The pilot commented that this traffic was over the center of the river, and the S-76 was flying the right shoreline, the pilot commented that TCAS was "working like a champ," referring to the display bearing accuracy.

The conflict was resolved without a maneuver. The light twin overtook the S-76 on the left. Comparison of the TCAS display with the visual scene prompted the pilot to comment on the excellent agreement.

3.2.3.4 Mission 121985A, New York Area. At 10:20:13 over Newark, ATC said "expect VFR traffic at Linden Airport." Several seconds later a TA was generated showing a TOP 400 feet lower in altitude closing from left-rear. The pilot maneuvered to the right slightly to visually acquire, then returned to course when the intruder was observed to be no factor.

3.2.3.5 Mission 121985B, Boston Area. At 13:29:20, a TA was generated on a twin engine Mooney. The TA display showed the target at 12 o'clock, -400 feet, and climbing. ATC called this traffic which was not visible against the skyline of the city of Boston. The Mooney was crossing the nose of the S-76 and eventually passed 0.2 miles to the right, 100 feet below. The pilot commented that he relied on TCAS to continually ascertain the position of the intruder in the event a maneuver was necessary. No maneuver was made, and the pilot commented further that this encounter was "a real confidence builder."

At 13:31:17, a helicopter (type unidentified) caused a TA, displayed as 12:00 2 miles, altitude unknown. The pilot acquired based on the TA and turned left to avoid an almost certain NMAC. After the incident, the pilot commented that the TA was correct and timely.

#### 4. SUMMARY - FAA PILOT RESPONSES COMPARED TO INDUSTRY OPINION.

From section 3, industry consensus contained seven key items relative to the cause of helicopter accidents, factors relating typical flight profiles, and recommendations to improve safety. These are paraphrased in table 4, and are compared to FAA test pilot consensus.

Generally, the FAA pilot responses agree with industry consensus. It, therefore, seems reasonable to expect that a helicopter TCAS as implemented in the S-76 can meet the needs of the helicopter community once the problem of display clutter generation due to ground traffic or multipath is resolved.

#### 5. DATA PRESENTATION - SURVEILLANCE DATA.

Helicopter TCAS must be capable of tracking threatening aircraft in order to issue timely traffic advisories. TCAS must do so constrained by interference limiting and a requirement that the false advisory rate be kept low.

In the subsections that follow, surveillance performance measures including protection volume size, track acquisition time, track reliability, and multipath rejection are all considered within the reduced interrogator power and increased scan period imposed by interference limiting. The intent of the analysis is to validate the draft MOPS surveillance requirements using flight data gathered in the east coast tour.

##### 5.1 PROTECTION VOLUME.

The following data on the geometry of the protection volume is used to determine the track distance required to ensure adequate TCAS protection.

Reference 6 (Helicopter User Survey) contains computed protection volumes for three typical geometries in helicopter operation. Figure 5 shows the cases developed in reference 6.

TABLE 4. INDUSTRY PILOT CONSENSUS COMPARED TO  
FAA PILOT OPINION

Industry Consensus, Item:	FAA Test Pilot Responses	Paragraph Ref.
1. Single pilot vs dual pilot operation.	In single pilot operation, pilot often becomes task saturated. <i>Audio prompt is necessary. False TA's can create a dangerous distraction.</i>	3.3.2.e
2. Leading cause of helicopter accidents - training/fatigue	En route, TCAS lessens workload. In terminal area, targets on ground may actually increase workload.	3.2.2.b, c, and d; table 3 Notes 2 and 8
3. Flight profiles - pilot tended to fly low.	FAA pilots stayed within height boundaries of VFR routes. Never experienced difficulty resolving encounters with turns.	3.2.3.1, 3.2.3.2, 3.2.3.5
4. Incidence of NMAC - most frequently observed in straight, level flight.	All of the encounters reported in this document occurred in straight, level flight.	3.2.3
5. Critical quadrant - left rear.	FAA pilots cited airframe members as visual obstructions. Three of the six encounters reported occurred from left rear.	3.2.3.3 3.2.3.4
6. ATC involvement - no factor in NMAC	In one of the six reported encounters, an ATC call was responsible for visual acquisition.	3.2.3
7. Pilot perceived NMAC risk.	FAA pilots cite the New York areas as a very dense and potentially dangerous area to fly. They rated TCAS as "necessary."	Table 3 Notes 2 and 3

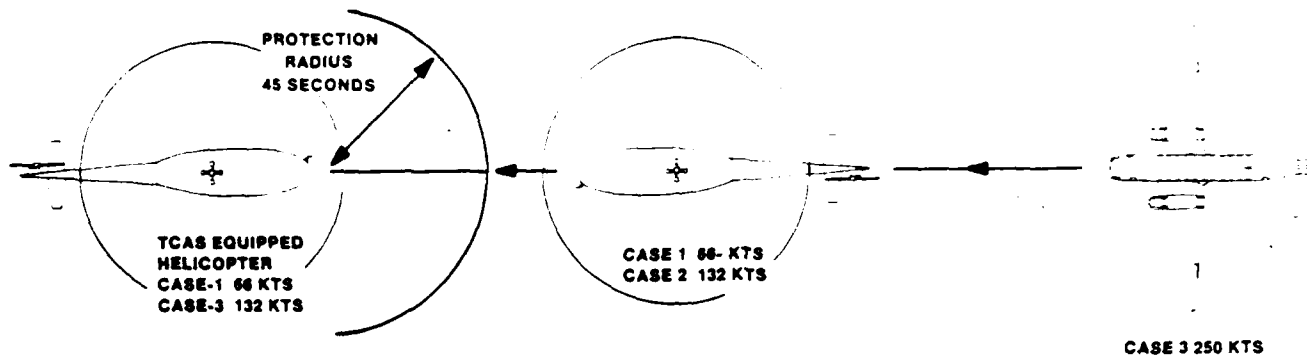


FIGURE 5. THREE SCENARIOS DEFINING TCAS PROTECTION VOLUME

Figure 5 shows a range of closing speeds which TCAS must be able to track. Closing speed coupled with advisory time defines the size of the protection volume. The authors of reference 6 used an advisory time of 45 seconds (after TCAS II) in their calculations, yielding the protection volumes shown in figure 5. In a practical TCAS however, the advisory time will probably be set to threshold at 25 seconds with an appropriate distance modification parameter (DMOD) (DMOD extends the advisory time two or three seconds, depending on closing speed).

It should be noted at this point that the draft TCAS I MOPS defines a minimum surveillance range of 4 nmi, but leaves the tau (TA) threshold and DMOD parameters unspecified. For purposes of this analysis, values of tau equal to 25 seconds and DMOD equal to 0.5 nmi (reference 7) will be used. An additional case will be added where the surveillance range is expanded to 5.0 nmi in order to provide a comparison to the minimum MOPS specification of 4.0 nmi.

Combining the information compiled thus far, it is possible to determine a minimum protection volume:

Let tau minimum = 25 seconds

Let range rate (RDOT) = 382 knots

Let DMOD = 0.5 nmi

then:

$$R = DMOD + (\tau \times RDOT) \div 3600$$

$$R = 0.5 + (25 \times 382) \div 3600$$

$$R = 3.15 \text{ nmi}$$

where R is the radius of the protection volume.



### 5.1.1 Estimated Time Required to Initiate Tracks.

In section 5.1 it was determined that tracks should be established against intruders as far away as 3.15 nmi so that a traffic advisory of at least 25 seconds duration can be provided.

The track initiation process cannot even begin until the intruder falls within the 4.0 mile range gate specified in the MOPS. Thus, TCAS must establish a track in  $(4.0 - 3.15) = 0.85$  nmi. For an intruder closing at 382 knots, that distance equates to 8 seconds. Using 5.0 nmi surveillance, TCAS I must establish a track in 17 seconds.

Eight (or 17) seconds may or may not be enough time to initiate a track given the MOPS requirement that a track is started only after three successive interrogation scans are answered by intruder's replies. Assuming perfect surveillance, every interrogation is answered. Real systems are not perfect. The probability of receiving three successive replies is a measure of the TCAS interrogator efficiency or "update rate (some texts also refer to interrogator efficiency as blip-scan-ratio)." The time to initiate an intruder track is directly related to update rate.

To estimate the time required to start a track requires a knowledge of the target update rate and interrogation scan period. Given these, the actual time can be estimated using a cumulative binomial distribution (reference 8) as developed in equations 1 through 4.

$$P_r \quad n \geq c = P_r(p, c, n) \quad (1)$$

$$P_r \quad x \geq c = \sum_{x=c}^n \binom{n}{c} (p)^c (1-p)^{n-c} \quad (2)$$

Equation 1 estimates the probability of obtaining three hits in exactly N scans.

Equation 2 estimates the probability of obtaining three hits in n scans. It is further modified (equation 3) by the condition that three "hits" occur consecutively with no interspersed misses.

$$P(AB) = P \ A \ P(B/A) \quad (3)$$

and becomes equation 4

$$P_r \quad n \geq c = P_r(p, c, n)$$

The definition of terms in equations 2 and 4 are:

c = number of scans to initiate track (= 3).

n = number of scans elapsed.

$P_m$  = update rate for scan m.

$1-p$  = miss rate.

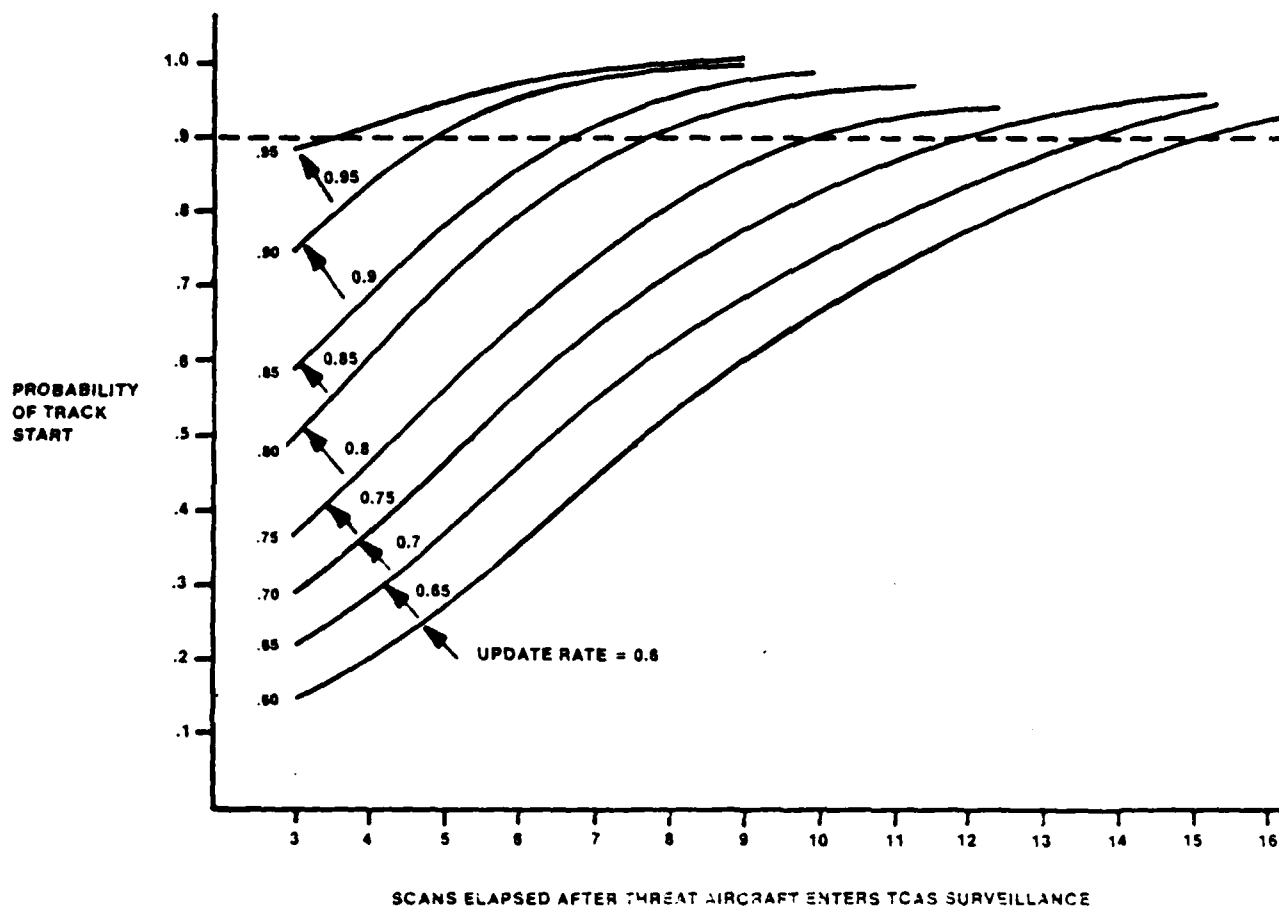


FIGURE 6: SCANS REQUIRED TO INITIATE TRACK VERSUS SURVEILLANCE UPDATE RATE

Equations 2 through 4 were used to compute the probability of starting a track versus update rate and scan count. The results are shown in figure 6. The portions of the curves above the dashed line include those conditions of update rate and scan count where the probability of starting a track is 0.9 or greater.

Returning to the high speed scenario (case 3, figure 5), it is now possible to compute the total possible advisory time within the MOPS specified surveillance range after accounting track initiation time. Table 5 contains computed advisory times versus update rate and interference limits for the minimum surveillance volume specified in the MOPS. In addition, two cases are added where the surveillance range is expanded to 5 nmi to increase the advisory time.

TABLE 5. TOTAL POSSIBLE ADVISORY TIME (IN SECONDS)  
VS INTERFERENCE LIMIT, UPATE RATE, AND  
SURVEILLANCE RANGE FOR A HIGH SPEED ENCOUNTER  
(CASE 3, FIGURE 2)

Update Rate	Scans to Start Track	Range Gate *in nmi	Total Possible Advisory Time in Seconds			
			Interference Limit Scan Period in Seconds			
			1	2	3	4
0.9	5	4.0	28	23	18	13
		5.0	39	32	17	22
0.8	8	4.0	25	17	9	1
		5.0	34	26	18	10
0.7	13	4.0	20	7	-	-
		5.0	29	16	3	-
0.55	17	4.0	16	-	-	-
		5.0	25	8	-	-

\*nmi denotes nautical miles

Legend:

0.9	28
	37

28 - Advisory time in seconds with 4.0 mile surveillance range.

37 - Advisory time in seconds with 5.0 mile surveillance range.

#### 5.1.2 A Means to Reduce Track Initiation Time.

The data in table 5 present quite clearly several cases that violate the MDPs requirements of surveillance range and track initiation criteria. The problem simply stated is: to provide reasonable advisory time; the surveillance range of 4.0 miles is too small when interference limiting is invoked because too much time is taken to initiate an intruder track. One proposed alternative is to increase the surveillance range, another (reference 9) to reduce the number of scans required to start a track.

##### 5.1.2.1 Advantage of Using Two Scans to Start a Track.

Equation 4 was again used to compute probability of track start versus update rate and scan count, this time requiring only two successive scans to start a track. Table 6 shows these results, and compares the data to the "three hit" case to illustrate the improvement.

TABLE 6. SCANS REQUIRED TO START TRACK,  
2 HITS COMPARED TO 3 HITS

Update Rate	Scans Required for 0.9 Track Probability	
	2 Hits	3 Hits
90%	3	5
85%	4	7
80%	5	8
75%	5	10
70%	6	13
65%	7	15

Table 6 shows that a track can be started in five scans with 75 percent update rate using two hits, compared to ten scans using three hits. Conversely, if a 70 percent update rate is maintained, six scans are required for the 2-hit case compared to thirteen scans for the 3-hit case.

#### 5.1.2.2 Potential for False Tracks Using 2-Hit Criteria.

The potential improvement in using only two successive hits to initiate a track is evident when considering just the delay in track initiation. However, there is possibly a very serious drawback to this approach and that is the false track proliferation which could result. To quantify this risk, knowledge is required of the "update rate" of false replies. These false replies are considered to be solely due to fruit and are, thus, uncorrelated.

To further this analysis, it is helpful to determine the probability that a false track will progress to impact the display status by being extended one or more times before coasting out. The MOPS requires deletion of a track if no valid reply is received in the three scans following the previous update or track initiation, whichever occurred last.

Thus, in determining the false track risk, it is necessary to determine the probability of track start, and the combined probability of track start and extension. Equations 5 through 7 give these probabilities based on 2-hit or 3-hit track start criteria and fruit update rate.

First, determine fruit update rate:

$$P_{fr} = F_r \times W_s \times R_g \times 12.6 \text{ s} \times (W_n + R_g) \quad (5)$$

where:

$F_r$  = number of fruit replies per second.

$W_s \times R_g$  = listening interval; whisper shout levels multiplied by the surveillance range gate.

$12.6 \mu\text{s}$  = conversion from range to radar time.

$W_n$  = reply correlation window (taken from reference 10).

Equation 5 will be used to compute the number of replies, per scan, which will be eligible for track formation or extension. The result of equation 5 will be used as update rate in equation 4.

Reference 11 contains a model for predicting airborne fruit rate (equation 6).

$$F = 150 \times N \quad (6)$$

TCAS 1 must be able to function in 0.08 aircraft density. In 30 miles that density equates to 226 aircraft. Of these, the majority are Mode C equipped and the remainder are non-Mode C. Density measurements in reference 12 show that the ratio is typically 3:1, Mode C to non-Mode C.

This analysis is concerned with false tracks due to non-Mode C aircraft. Therefore, the fruit rate will be calculated using non-Mode C only as follows:

$$\begin{aligned} f &= 226/3 \times 150 \\ f &= 75 \times 150 \\ &= 11,280 \text{ replies/second.} \end{aligned}$$

Substituting  $f$ , equation 6 for  $f_r$  in equation 5, a fruit update rate for false tracks is computed in equation 7:

$$\begin{aligned} P_{fr} &= 11,280 \times 4 \times 4.0 \text{ miles} \times 12.6 \text{ } \mu\text{sec} \times W_n \div 4.0 \\ &= 0.568 \times W_n \end{aligned} \quad (7)$$

The term  $W_n$  is either 0.619 or 0.102 depending on the current scan. In the first and second scans,  $W_n = 0.619$ ; in the third scan  $W_n = 0.102$ . (This is a characteristic of Lincoln's surveillance subsystem - reference 10.)

Therefore,

$$P_{fr} = 0.352 \text{ scans 1, 2}$$

$$P_{fr} = 0.058 \text{ scans 3}$$

The probability of starting a track using the 3 hit criteria is then:

$$\begin{aligned} P_{fr} &= (0.352 \times 0.352 \times 0.352) \times 0.058 \\ &= 0.113 \times 0.058 \\ &= 0.0066 \end{aligned}$$

or 1 false track every 151 scans.

Using the 2-hit criteria, no velocity prefilter may be applied as is done in the 3-hit criteria. Therefore, the correlation window size must be increased to 0.333 nmi. The term " $W_n$ " in equation 5 becomes 0.333; all other terms remain the same as the 3-hit criteria.

$$P_{fr} = 0.189 \quad \text{2-hit criteria}$$

Using this value in equation 4, the probability of starting a false track is:

$P = 0.035$ ; or 1 track every 28 scans

2-hit case - every 28 scans

3-hit case - every 151 scans

Turning attention to false track extension, equations 2 and 5 may be used to compute the probability of receiving "C" replies in "M" scans. In this problem,  $C=1$  and  $M=3$  (equation 2) because only one reply in three scans is required to extend track. Smaller correlation windows, taken from reference 10, are used in equation 5.

$$P_{te} = P_r \cdot x_{\geq c} \text{ (where } p = 0.133; \text{ equation 2)}$$

where  $P_{te}$  = probability of one extension

$$P_r \cdot x_{\geq c} = \text{results of equation 2}$$

The probability of extending a false track in M times is:

$$P_{te} = (P_{te})^M$$

Combining equations 2, 5, 6, and 7 yields:

$$\begin{aligned} P_{te} &= 0.31 \\ P_{te} &= 0.096 \\ P_{te} &= 0.029 \\ P_{te} &= 0.009 \end{aligned}$$

These results show that the probability of extending false tracks based on random fruit replies starts out reasonably high, but then vanishes rather quickly. However, it should be remembered that each update extends track life at least three scans.

As each scan can last 4 seconds, a false track updated only once can exist long enough to impact display status for at least 12 seconds; long enough to attract the pilot's attention.

#### 5.1.2.3 A Method of Reducing False Tracks.

The method suggested in reference 10 for the reduction of the multiple replies elicited during a Whisper Shout (WS) interrogation sequence. When multiple replies are received, they are combined into a single target report. This process is called defruitting.

The effect of defruitting can easily be computed because the process essentially "squares" the fruit update rate. Thus, using the methods of section 5.1.2.2 the following results are obtained:

With track initiation in two scans:

1 false track every 816 scans, and

$P_{te1} = 0.051$

$P_{te2} = 0.002$

These results show the dramatically reduced likelihood of false track generation and extension, using defruitting.

The success of defruitting depends heavily on the reply efficiency of real aircraft. The determination of the value is made from observations of actual flight data. The discussion is contained in section 5.2.

### 5.1.3 Probability of Track.

In the previous section, the topic of track initiation was examined. In this section, attention is turned to the likelihood of maintaining a track once started.

The analysis of the previous section was based on update rate; that is, the ratio of received replies to interrogation scans. The analysis in this section employs the same technique and as such is based on equation 2.

In order to maintain track, at least one valid reply (update) must be received with no more than three elapsed scans since the previous update. But the update order is not critical; the reply may be received in any of the three scans. The fact that the order of update is not critical is the reason that equation 2 suffices for this analysis.

Using equation 2, probability of track was computed versus rate. The results are shown in figure 7.

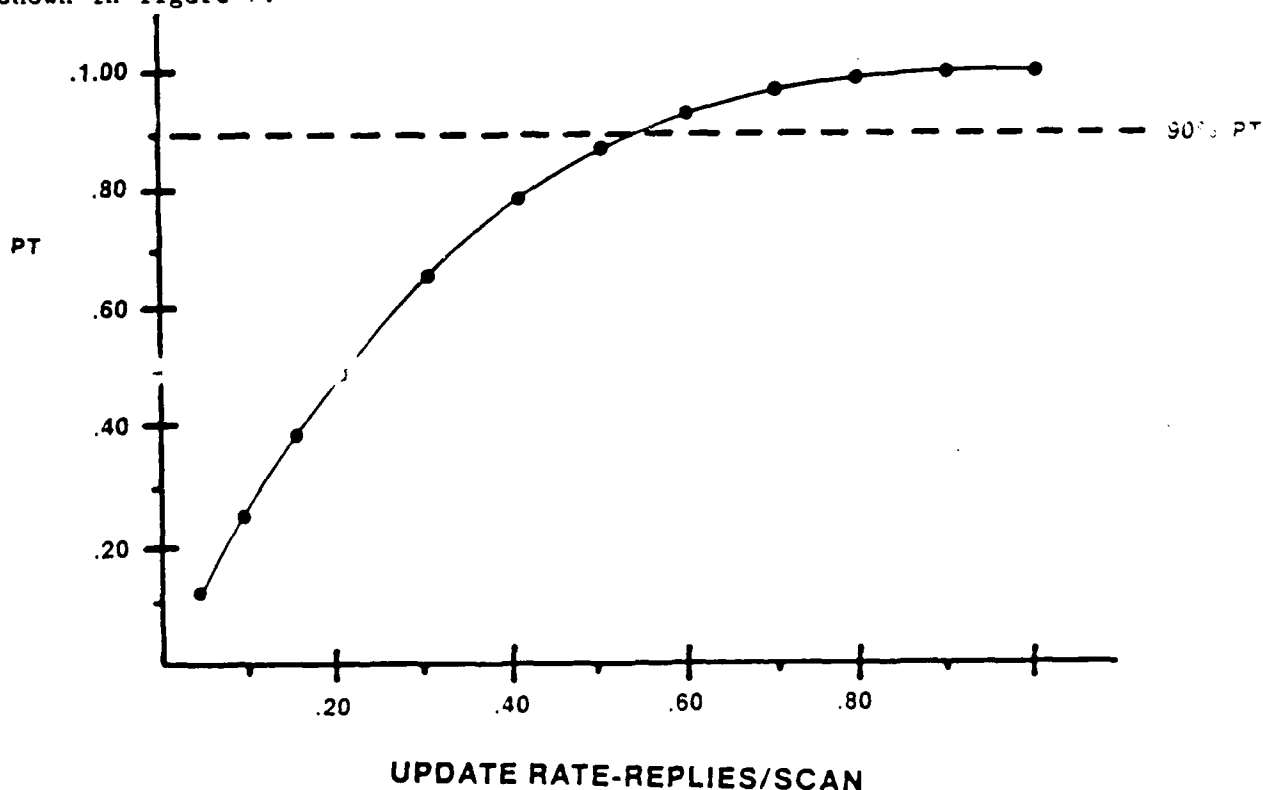


FIGURE 7. PROBABILITY OF TRACK (PT) VERSUS UPDATE RATE

As seen from figure 7, rather high probabilities of track can be expected from only mediocre update rates. In fact, probability of track reaches 0.90 at slightly less than 0.55 update rate (as indicated by the dashed lines in figure 7).

In the next section (5.2) realizable update rates versus interrogation power are determined. That data will give meaning to the results of this section by linking update rate, the basis of this section's analysis, to interrogator power.

## 5.2 DETERMINATION OF UPDATE RATE.

Flight data from each of the cities toured by the S-76 were filtered for occurrence of Mode C and non-Mode C tracks. Raw reply data was then correlated, on a per second basis, to the track files in the corresponding mode. In this way the presence or absence of correlating replies during each track second accumulated to a measure of update rate versus range and WS level. This correlation process was then repeated, this time with the additional condition that at least two replies must exist in each track second, in order to measure update rate when defruitting is employed.

This section also contains surveillance data from Group 2 flights, which consisted of planned encounters against one or two Technical Center aircraft. The planned encounter data will be used as a baseline for comparison to the data from the cities tour.

### 5.2.1 Update Rate - Planned Encounters.

5.2.1.1 Data Presentations. Twenty-nine encounters were flown. They include 25 single-intruder and 4 multiple intruder encounters. Convergence angles, as shown in figure 8, were derived from near NMAC and actual midair collision scenarios (reference 1). These angles include directions where antenna coverage is somewhat limited due to fuselage shielding.

Figure 9 shows Mode C update rate as a function of range, for four different combinations of interrogator power, defruitting, and WS step.

Figure 10 shows update rate as a function of WS level and defruitting over a surveillance range of 5 nmi.

Figure 9 consists of four parts, 9a through 9d. The graphs denoted 9a and 9b show update rate for the six lowest WS steps (9a) and full bottom (9b) antenna interrogation sequences. Graphs 9c and 9d show update rate for the six lowest WS steps (9c) and full bottom (9d) antenna interrogation sequence.

Graphs 9a and 9b were developed based on the Technical Center's Group 2 rotorcraft TCAS effort. That work determined analytically that the peak power contained in the lowest six WS levels of the TEU interrogation sequence should be sufficient to provide adequate surveillance. Therefore, graphs 9a and 9b were developed specifically to validate the previous analysis.

Graphs 9c and 9d were developed to utilize the full top and bottom antenna interrogation sequences. This data set provides a comparison to the lower power case developed in 9a and 9b.



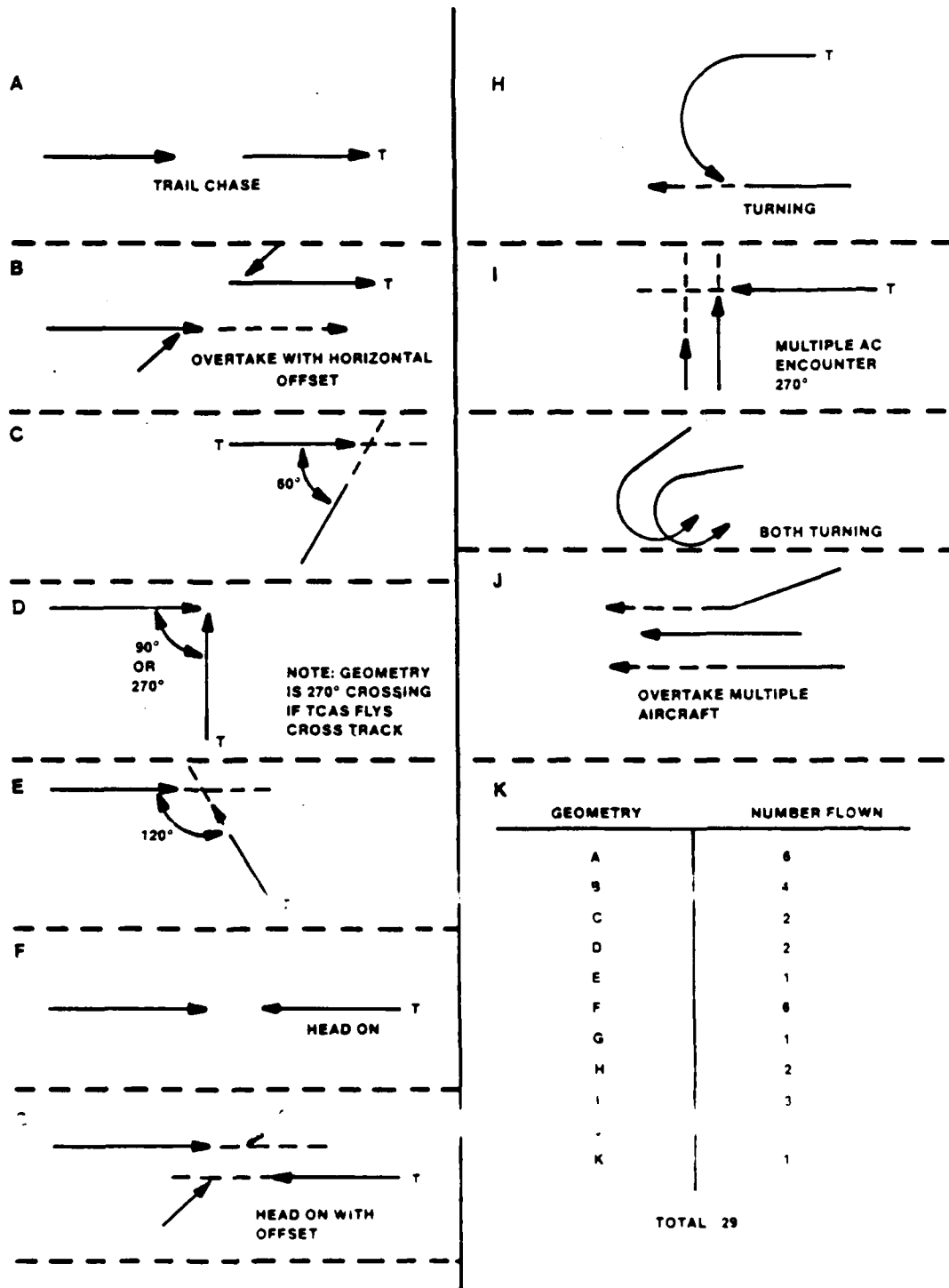


FIGURE 8. ENCOUNTER GEOMETRIES

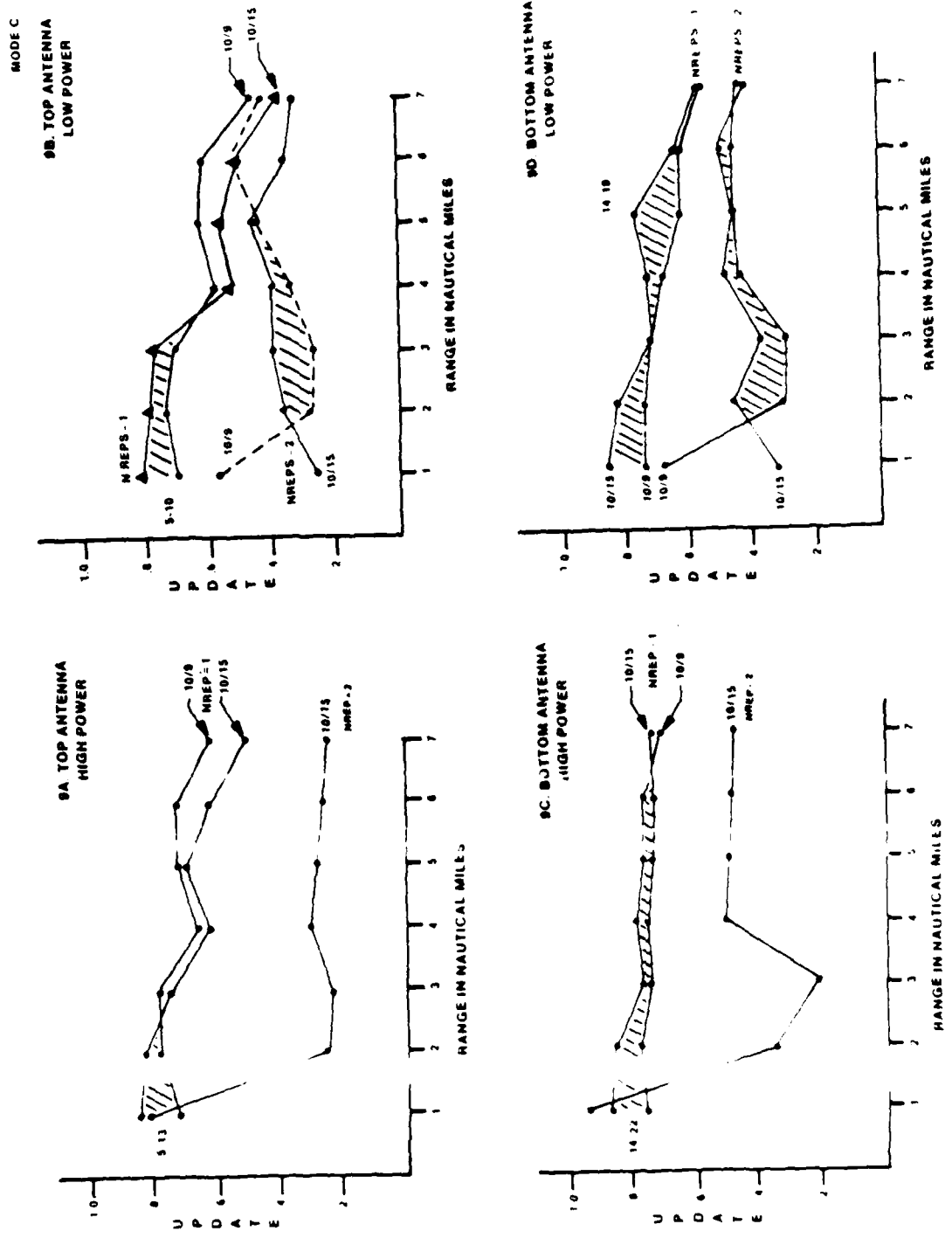


FIGURE 9. UPDATE RATE VS RANGE FOR FAA ENCOUNTER AIRCRAFT

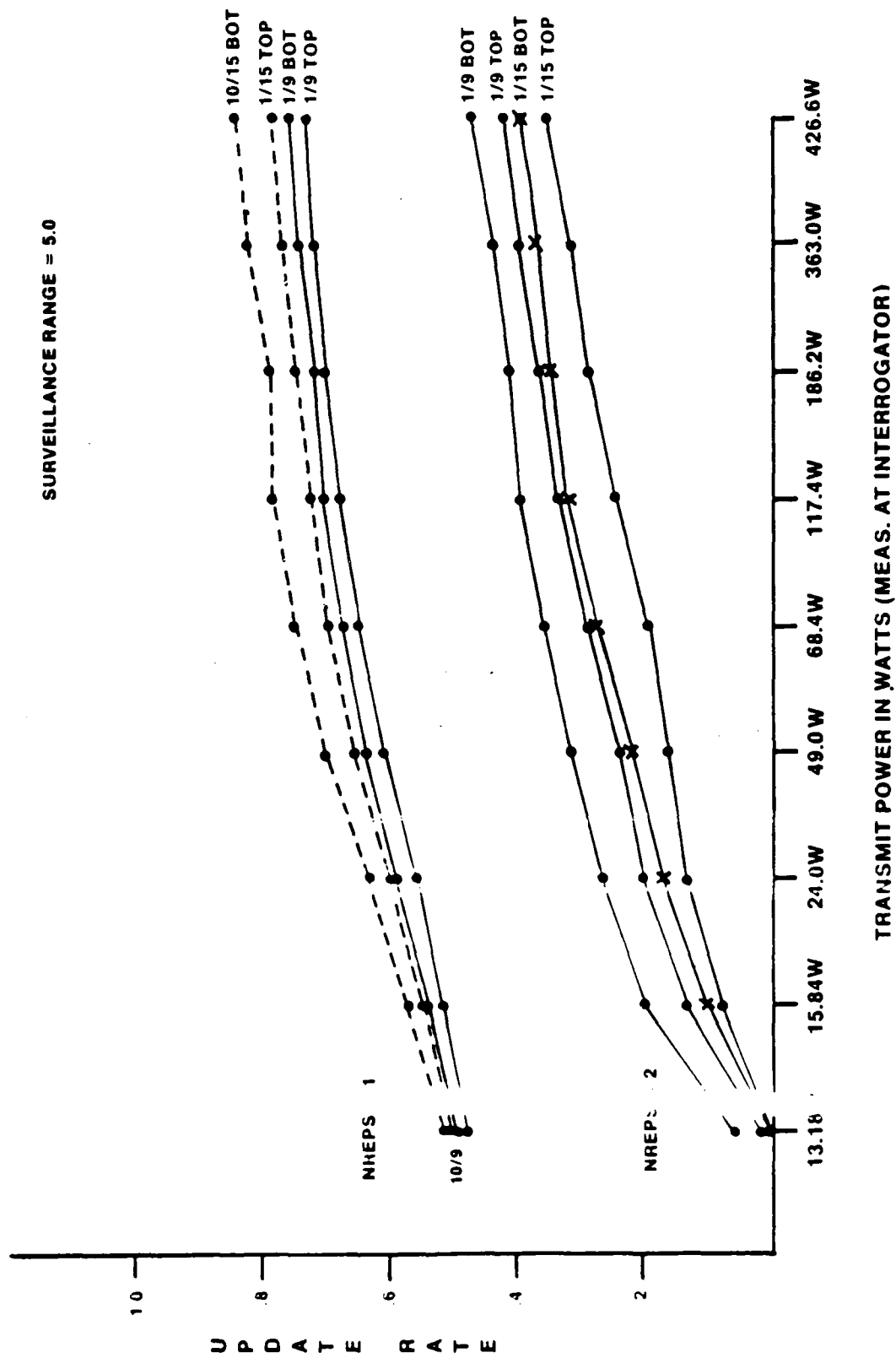


FIGURE 10. UPDATE RATE VS INTERROGATOR POWER FOR FAA ENCOUNTER AIRCRAFT

Figure 10 provides the link between the lower power case of 9a and 9b, and the high power case of 9c and 9d, by showing the increase in update rate as increasingly higher power is transmitted.

5.2.1.2 Data Analysis - Track Initiation. The proposed TCAS I MOPS limits the maximum interrogator power in a baseline TCAS I to 167 watts peak in a single second. An enhanced TCAS I with the capability to transmit Mode S broadcast signals may interrogate with up to 250 watts in a single interrogation. The analysis in this section concentrates on update rate based on these two power levels; making use of the data presented in section 5.2.1.1. Note that the two data sets presented in figures 9a and 9b correspond to the baseline TCAS I case and the data presented in figures 9c and 9d correspond to the enhanced TCAS I case.

It is necessary to compute the rate-power product for the TEU interrogation, and compare to the MOPS requirement. Considering the noninterference limited case for baseline TCAS I:

$$\begin{aligned} WS_k &= 13.1W + 15.85W + 24W + 49W + 68.4W + 117W \\ &= 287.3W \end{aligned}$$

Thus, the TCAS interrogator sources 287.3 watts peak. Accounting for cable losses, the peak power delivered to the antenna is computed.

Cable losses in the S-76 = 2.7 dB

$$\begin{aligned} P_{ant} &= 287.3 \text{ watts} \times \text{cable loss} \\ &= 24.6 \text{ dBw} - 2.7 \text{ dB} \\ &= 21.88 \text{ dBw} \\ &= 154 \text{ watts} \end{aligned}$$

In the enhanced TCAS I, the power delivered to the antenna is:

$$\begin{aligned} P_{ant} &= WS_k \times \text{cable loss} \\ &= (\sum WS_k + 287.3W) \times \text{Cable Loss} \\ &= (287.3W + 186.2W + 331W + 426W) \times \text{cable loss} \\ &= 30.9 \text{ dBw} - 2.7 \text{ dB} \\ &= 660 \text{ watts} \end{aligned}$$

In table 7 these results are compared to the MOPS requirements.

Table 7 compares the MOPS requirements when using a 1-second (or more) interrogation period.

The estimated time to initiate track can be computed from the results of section 5.2.1.2 and the data contained in figure 9. These track initiation times are contained in table 8. Minimum and maximum times are specified in table 8 on calculations based on two data sets, October 9 and 15, 1985. Table 8 shows no real gain in using 2-hit track initiation with defruitting, because update rates for this case were so much lower than the nondefruitted (3-hit case).

TABLE 7. EXPERIMENTAL TEU WS SEQUENCE VS MOPS REQUIREMENTS

<u>MOPS Definition</u>	<u>MOPS Requirement For Antenna - Input Power: Rate - Power Product*</u>	<u>Actual Antenna Input Power: Rate - Power Product</u>
TCAS I	167W	154W
TCAS II	2430W	660W

\*Noninterference limited; based on 1-second measurement

Table 8 shows another rather interesting result. That is, the time required to initiate a surveillance track changes very little from the minimum TCAS (low power) case to the enhanced TCAS (high power) case. This result means that the decrease track initiation time. Figure 10 illustrates this. From 117.4 watts (minimum TCAS) to 426.6 watts (enhanced TCAS), the gain in update rate is about 8 percent for each curve. Table 6 predicts that difference causes a two-scan reduction in track initiation time.

The gain realized by the increased interrogator power occurs at surveillance ranges beyond 5 nmi. Such ranges are not included in this document.

5.2.1.3 Data Analysis - Track Extension. Using the update rates shown in figure 9, it is determined from figure 7 that the probability of track exceeds 0.9 over a surveillance range of 5.0 nmi for the minimum TCAS I and enhanced TCAS interrogation sequences.

#### 5.2.2 Update Rate - Targets of Opportunity.

5.2.2.1 Data Presentations. Figure 11 shows Mode C update rate versus range for four combinations of interrogator power, defruitting, and top antenna/bottom antenna interrogators. These data were accumulated in the Terminal Cities of Philadelphia, Pa., Washington, D.C., New York, N.Y., and Boston, Mass.

Figure 12 shows update rate as a function of transmitter power and defruitting over a surveillance range of 5 nmi.

#### 5.2.2.2 Data Comparison - Planned Encounters vs Targets of Opportunity.

Comparison of figures 9 and 11 shows a slightly higher update rate obtained in planned encounters versus the chance encounters from 0 to 4 miles range. Beyond 4 miles, the update rate is generally higher.

A second comparison of figures 9 and 11 shows that the planned encounter update rates tail off 20 to 30 percent in the lower power transmit sequence, and remain "flatter" using the high power transmit sequence. This is especially true in the data from the October 15, 1985, flight. The data in figure 11 generally exhibit the same tail but follows the trend of the October 9, 1985, data more closely.

A word about the test aircraft used in the planned encounters is appropriate. On October 9, 1985, all the encounters were flown using the Center's Aerocommander, a twin-engine aircraft equipped with a "Part B" transponder, i.e., typical of air carrier units. The October 15, 1985, mission was flown predominately with a Cessna 172 equipped with a "Part A" transponder typical of general aviation (GA).

TABLE 8. TRACK INITIATION - NUMBER OF SCANS REQUIRED FOR  
0.9 PROBABILITY OF TRACK INITIATION

<u>Case</u>	<u>Update Rate</u>	<u>Track Initiation Criteria</u>	<u>Antenna</u>	<u>Defruitting</u>	<u>Track Initiation Number of Scans to Start Track</u>
Note 1	0.72 min	3 hits	Top	No	>10 minimum 7 maximum
	0.82 max	3 hits			
	0.72 min	3 hits	Bottom	No	>10 minimum 7 maximum
	0.85 max	3 hits			
Note 2	0.72 min	3 hits	Top	No	10 minimum 7 maximum
	0.85 max	3 hits			
	0.74 min	3 hits	Bottom	No	9 minimum 7 maximum
	0.87 max	3 hits			
Note 1	0.27 min	2 hits	Top	Yes	>10 minimum 8 maximum
	0.58 max	2 hits			
	0.32 min	2 hits	Bottom	Yes	>10 minimum 6 maximum
	0.68 max	2 hits			
Note 2	0.22 min	2 hits	Top	Yes	>10 minimum >10 minimum
	0.30 max	2 hits			
	0.21 min	2 hits	Bottom	Yes	>10 minimum 9 maximum
	0.51 max	2 hits			

Notes:

1. Data shown are for minimum TCAS I.
2. Data shown are for enhanced TCAS I (TCAS II)

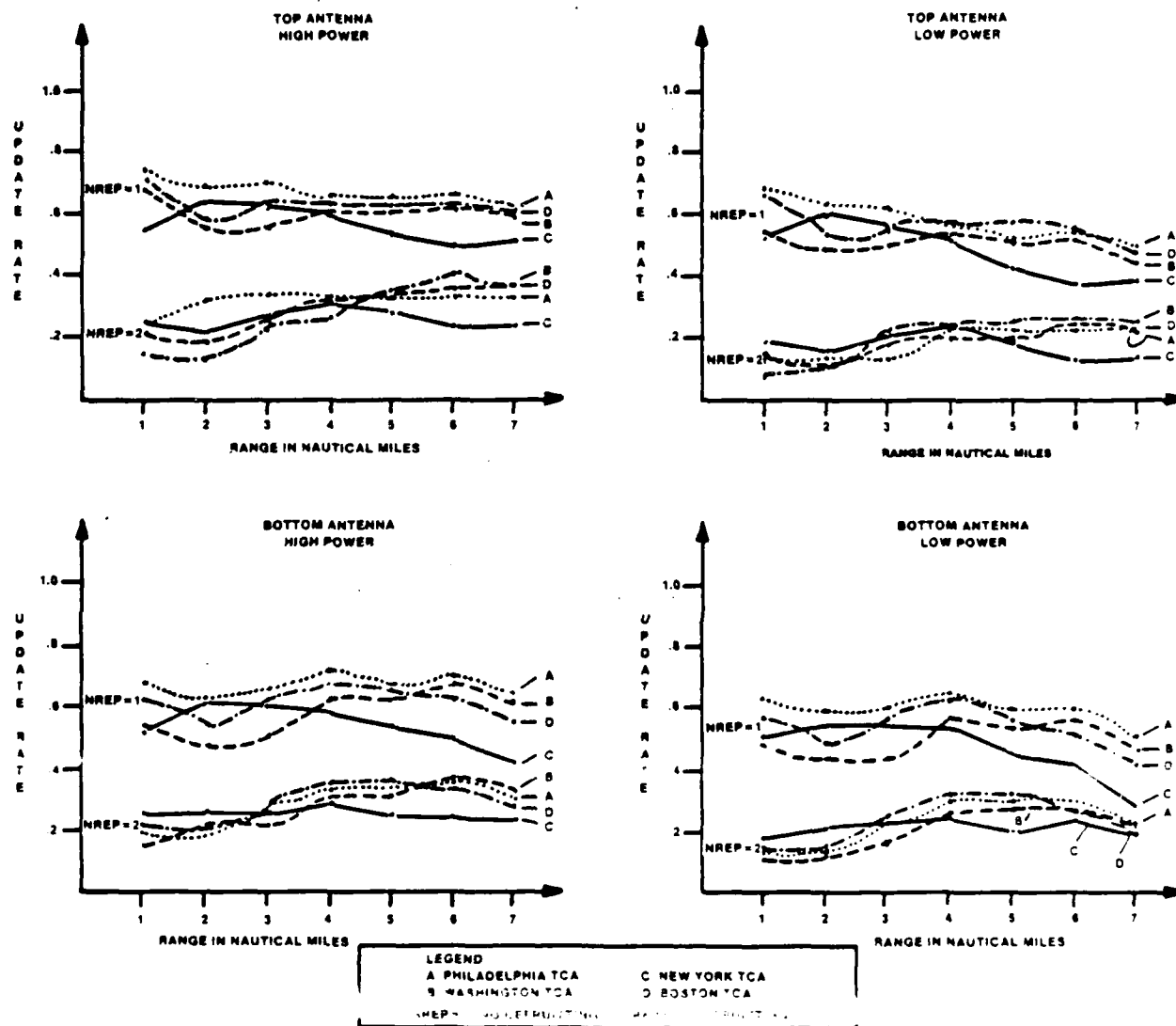


FIGURE 11. UPDATE RATE VS RANGE FOR TARGETS OF OPPORTUNITY

NOTE: NREP=1: NO DEFRUITTING  
NREP=2: DEFRUITTING

NOTE: UPDATE RATE (PROBABILITY OF UPDATE)  
ACCUMULATED OVER A SURVEILLANCE RANGE  
OF 0 TO 5 NAUTICAL MILES (NMI)

LEGEND: A PHILADELPHIA TCA  
B WASHINGTON TCA  
C NEW YORK TCA  
D BOSTON TCA

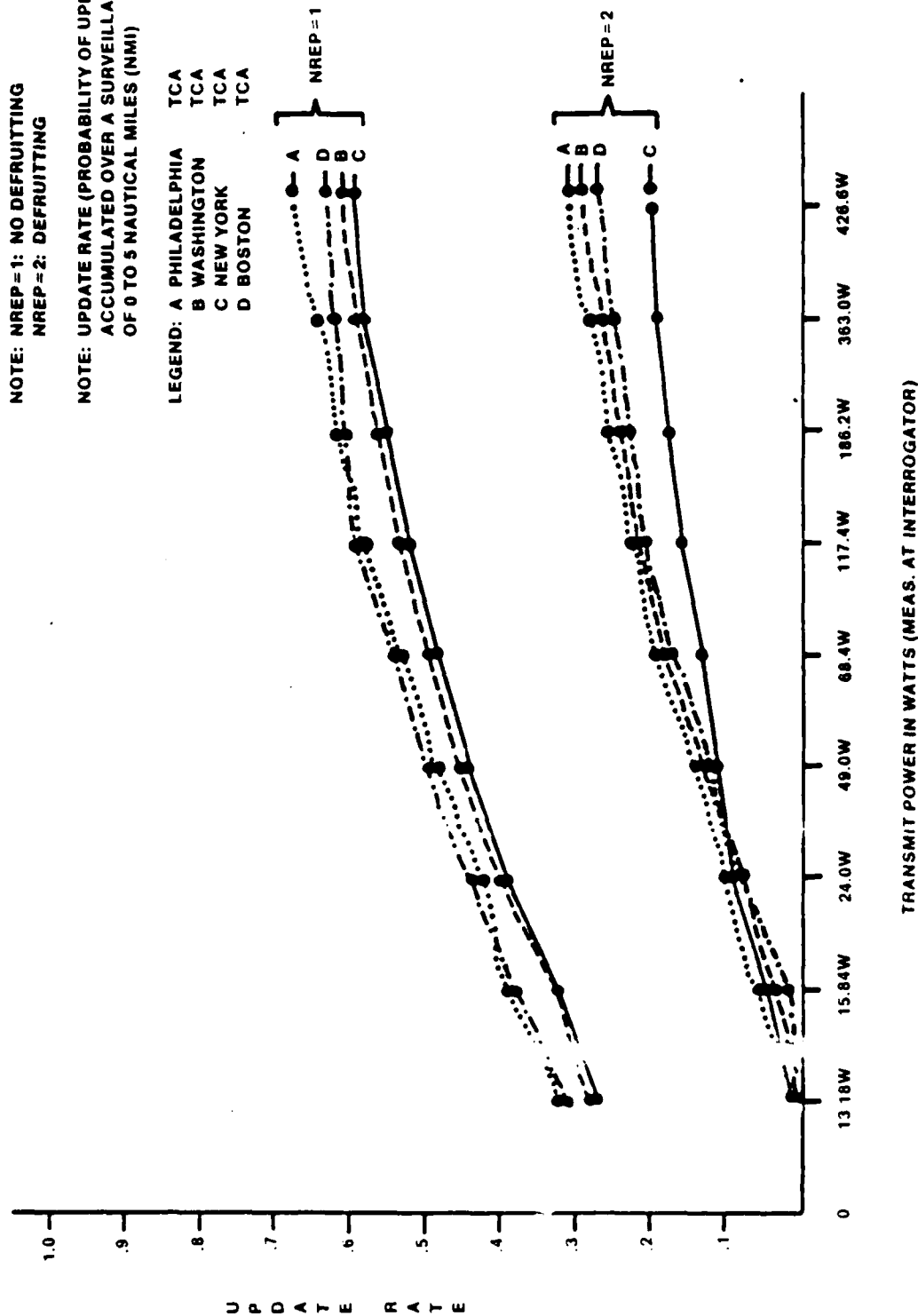


FIGURE 12. UPDATE RATE VS INTERROGATOR POWER FOR TARGETS OF OPPORTUNITY



units. The two main differences in air carrier vs GA transponders are transmit power and receiver sensitivity. The differences in transponder types account for the shape of the curves in figures 9a and 9b, and also explain why the data in figure 11, mainly air carrier data, aligns with the October 9, 1985, data in figure 9.

5.2.2.3 Track Initiation - Targets of Opportunity. From figure 11, track initiation times were computed for the defruitted case and the nondefruitted case. These times range from 12 scans (nondefruitted, Philadelphia, TCA) to 15 scans (Washington TCA, nondefruitted).

Combining table 6 and figure 11, track acquisition times for the defruitted case range from >10 scans for Boston to >12 scans for the New York TCA.

As in the planned encounter data, no real benefit was realized in using defruitted replies, due to the low reply update rate.

Once again, as in the planned encounter data, the minimum TCAS I interrogation sequence provides adequate surveillance, compared to the enhanced TCAS I case.

5.2.2.4 Probability of Track - Targets of Opportunity. The probability of track remains above 0.90 for the nondefruitted case, and drops to an average of 0.70 for the defruitted case.

5.2.2.5 Interrogation - Reply Link Margin. In figures 10 and 12, the observed update drops slightly from the enhanced to the minimum TCAS I cases. Update rate begins to drop significantly at 49 watts and below. These results yield a link margin of 8 dB for the enhanced TCAS I and 2 dB for the minimum TCAS I.

## 6. DATA PRESENTATION - TRAFFIC ADVISORY DATA.

In this section the performance of the traffic advisory logic installed and flight tested in the TEU is evaluated. The evaluation attempts to determine the suitability of the logic to the helicopter environment. Data from several east coast cities are analyzed via playback of flight data three, a CAD logic model (see also section 1.5). Observer notes taken from flight log help to focus the analysis.

The installed logic was taken from the TCAS II MOPS; tau driven with  $\tau_{MOP} = 0.4$  and TA threshold (TATHR) = 35 seconds (see also section 1.4).

### 6.1 ANALYSIS APPROACH.

As a starting point TEU flight data, including ATOCRBS track and raw reply data, were assembled into a data base and screened for those intruder tracks which met the display requirements of a baseline TCAS I system (for reference see table 1).

The same data base was further screened for only those tracks which met the installed TA logic criteria. In an enhanced TCAS I these tracks would cause TA's with the associated amber TA display and aural alerting. This screening includes all TA eligible tracks, some of which are valid, some are false created by fruit, some are multipath, etc. Each case is considered

individually; for valid tracks, optimization of the TA logic is considered; for fruit or multipath generated tracks, the existing nuisance rejection logic is evaluated and improvements suggested if applicable.

## 6.2 BASELINE TCAS I.

A baseline TCAS I is designed to show all traffic within its surveillance range. Traffic is shown on a proximity basis; that is no display coding employed to identify threatening aircraft from nonthreat aircraft in the vicinity. In areas of heavy traffic density, the display can get very cluttered very fast, as witnessed by pilots and observers who used the "all-prox" feature while flying in the S-76.

## 6.3 ENHANCED TCAS I.

Enhanced TCAS I makes provisions for prioritization of intruder traffic to prevent display clutter. The premise of the threat prioritization logic is the ability to predict the safe or unsafe passage of an intruder aircraft based on his tracked position and velocity vector. The quality of the prediction (a subject of various papers) is generally measured by comparing the intruder's predicted future position with the actual position some fixed time later at the point of closest passage. It is this measure that will be used in the paragraphs to follow.

Figure 13 shows the range and relative altitude, at their closest point of approach (CPA), of all aircraft that ventured within 4.0 nmi of the TEU. In the figure, two regions are highlighted. The shaded region bounds all aircraft considered to be genuine threats and, thus, would qualify for TA status. The hashed region shows the altitude filter and DMOD parameters currently implemented in TCAS II, sensitivity level 5.

Figure 13 shows only valid aircraft data; no fruit tracks or multipath effects are included because the data in the figure will be used to optimize the TCAS I TA Logic. It is assumed that the nonvalid tracks will be eliminated before progressing to impact display status.

### 6.3.1 Traffic Advisory Logic Optimization - the Range Test.

One of the effective techniques for threat detection is the use of a tau threshold (reference 13). Tau represents the predicted future time when an intruder aircraft will penetrate a sphere surrounding the TCAS aircraft. In TCAS II, the radius of the sphere is parametrically dependent on altitude and is called "DMOD."

The variable tau is also an altitude dependent parameter in TCAS II. When its computed value drops below some threshold, e.g., 35 seconds, TCAS II issues a TA. Thus, tau is maintained as part of each intruder's track file (ITF) and is updated each scan period.

TCAS II tau is computed according to equation 8:

$$\tau = \frac{R_n - \text{DMOD}}{\text{RDOT}_N} \quad (8)$$

LEGEND:  
 B=BOSTON  
 Y=NEW YORK  
 D=WASHINGTON

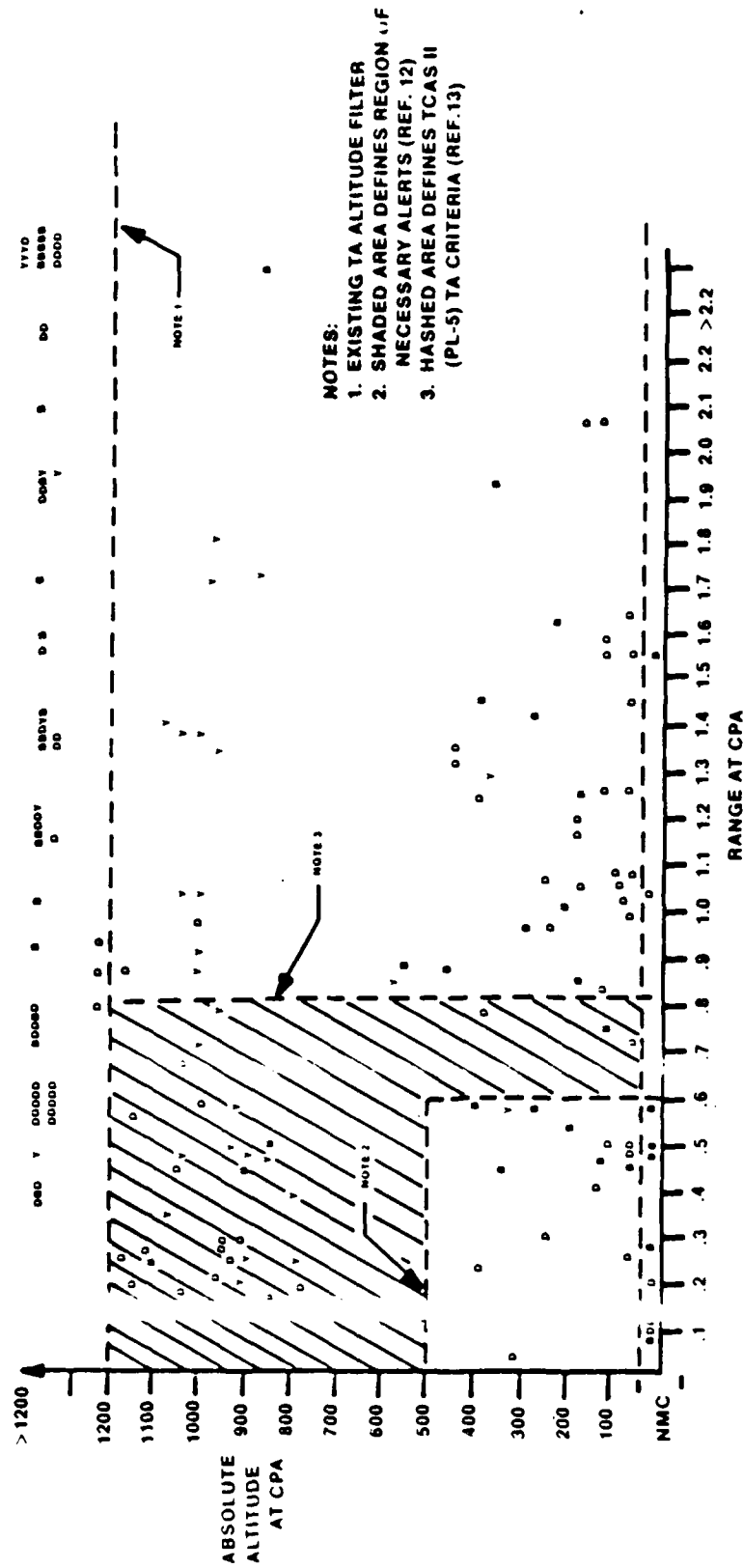


FIGURE 13. RANGE AND RELATIVE ALTITUDE AT CPA OF ALL AIRCRAFT WITH MODIFIED TAU=435 SEC. NO ALTITUDE FILTER EMPLOYED

Where:

Rn = ITF range measurement  
at the Nth scan  
RDOT = Smoothed ITF closing  
rate at the Nth  
scan

In the TCAS II TA logic, DMOD is used to protect against very slowly converging intruders who would not otherwise satisfy the TAU criterion. Except for the slow convergence case, DMOD usually has a small effect on the size of the tau protection volume because closure speeds associated with TCAS II are several hundred knots. At slower closure speeds, the effect of DMOD on tau can be magnified. Figure 14 shows how DMOD, as used in equation 8, increases the size of the tau protection volume. Figure 14 shows that for low values of closing rate (e.g., 100 knots) the protection volume is almost doubled.

Figure 15 shows a histogram of closure rates of all targets of opportunity (TOP) and only those TOP who passed within +1200 feet relative altitude of the S-76. Figure 15 shows fairly heavy concentration around 90 kts, with a secondary mode at 190 kts. These results agree with reported airspeeds from reference 5. Comparison of figure 15 with figure 14 shows the increase in tau protection volume (equation 8) for values of DMOD from 0.1 to 0.5. At 90 kts, DMOD contributes from 5 seconds (0.1 nmi) to 20 seconds (0.5 nmi). At 190 kts, DMOD contributes from 2 seconds to 10 seconds. This increase of protection volume due to DMOD means that aircraft which would normally cause alerts at 25 seconds prior to CPA will actually alert at 30 to 45 seconds prior to CPA, assuming 90 kt closure and DMOD range from 0.1 to 0.5 nmi. The benefit is increased warning time; the detractor is an increase in unnecessary alerts.

Returning to figure 13, the region of necessary alerts is shown in the shaded region (reference 14). Excluding for a moment the effects of DMOD, the minimum attainable tau for 90 kts closure rate is (using equation 8):

$$\begin{aligned}\tau &= \frac{\text{Range} - \text{DMOD}}{\text{RDOT}} \\ &= \frac{0.5 \text{ nmi} - 0}{90 \text{ kts} \times \frac{1 \text{ hr}}{3600 \text{ sec}}} \\ &= 20 \text{ seconds}\end{aligned}$$

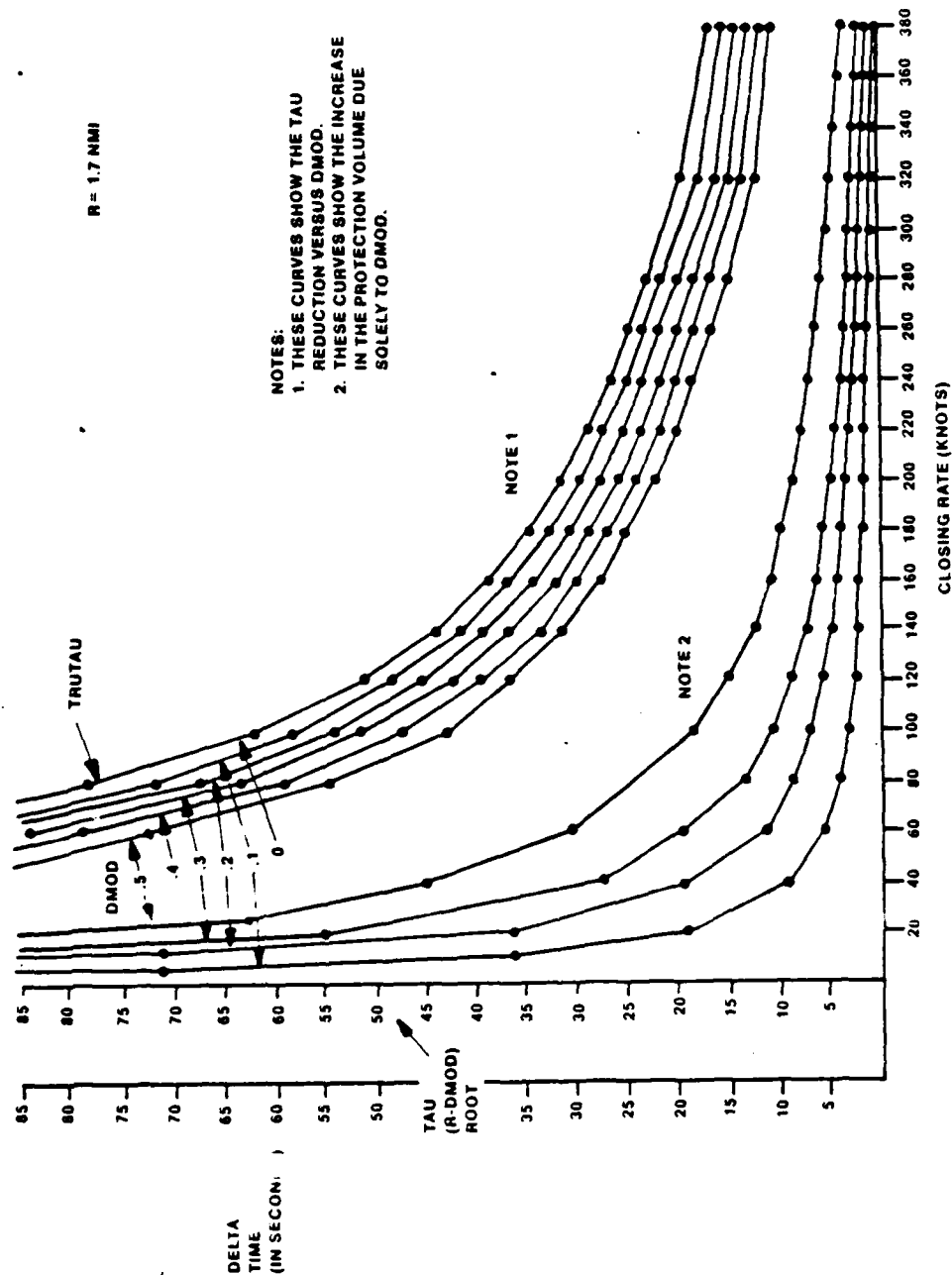


FIGURE 14. THE EFFECT OF  $D_{MOD}$  ON  $\tau$

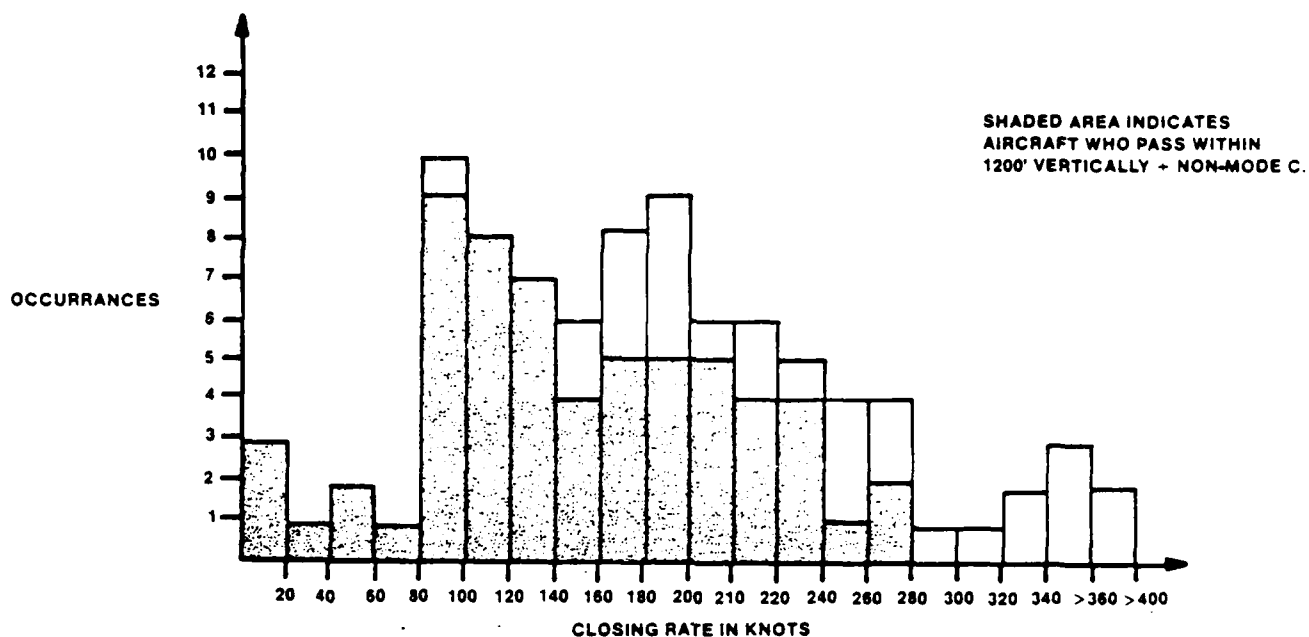


FIGURE 15. CLOSING RATE DISTRIBUTION OF TARGETS OF OPPORTUNITY

Thus, necessary TA's will have tau minima of 20 seconds or less. Figure 16 shows a histogram of minimum achieved tau values (DMOD = 0) for all TOP and only those that passed within  $\pm 1200$  feet relative altitude. In figure 16 this example applies to data from 20 seconds to 40 seconds, accounting for 31 percent of all TOP and 55 percent of all TOP which passed within  $\pm 1200$  feet.

To summarize the results thus far, figures 13 through 16 show that the TCAS II protection volume increases as the closure rate of a threat aircraft decreases. The increase in protection volume may be inappropriate in the helicopter flight regime because the unnecessary TA rate may become excessively high.

A more useful approach is to provide more warning time against distant, rapidly converging intruders, and less time against closer, slower threats. This rationale is based on the assumption that closer threats are easier to see. Less time spent in acquisition means more time for avoidance.

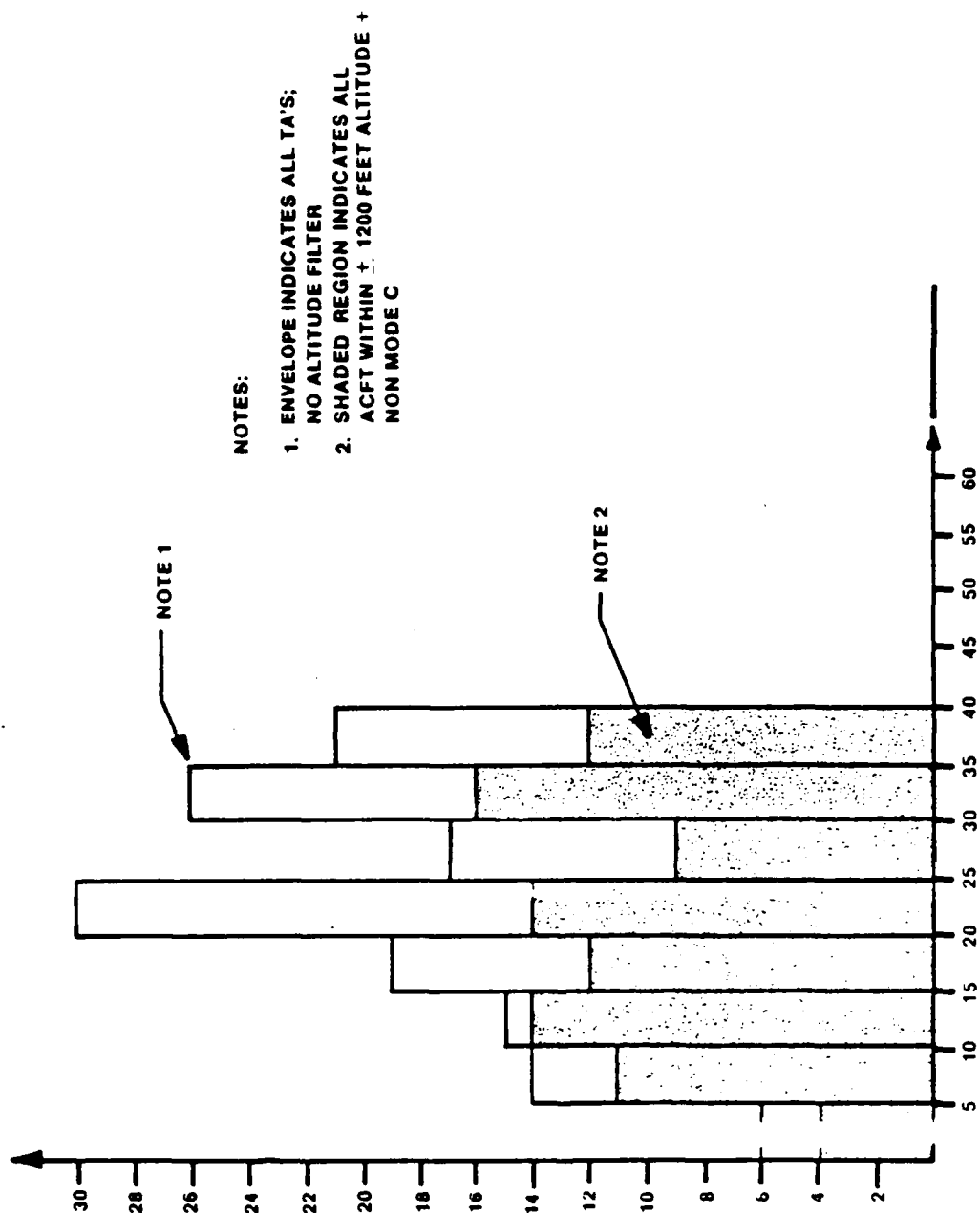


FIGURE 16. MINIMUM ACHIEVED TAU FOR THREAT AND NON-THREAT AIRCRAFT

Equation 9 is an alternate method of computing tau. It is the same as equation 8 except that DMOD is added to rather than subtracted from the range measurement.

$$\tau = \frac{ITFR_N + DMOD}{ITFRDOT_N} \quad (9)$$

Where ITFR and ITFRDOT are the same as equation 8.

Figure 17 is a graphic presentation of equation 9, showing the reduction in protection volume (TRTAU) versus closing rate and DMOD. The bold line denoted (R=0.5 nmi) represents an arbitrary sphere of radius 0.5 nmi placed around the TCAS aircraft. Any aircraft penetrating this sphere would unconditionally qualify for a TA. The effect of the sphere on warning time is illustrated by the dashed portion of the curves. In linear flight the dashed region is impossible to enter. Thus the sphere protects against dangerously short warning times.

The curves in figure 17 show that warning time (i.e., protection volume) decreases with decreasing closing rates. This is exactly the desired effect in light of figure 17. Using a DMOD of 0.3 nmi in equation 9, the warning time around 90 kts is approximately 22 seconds. The desired effect is achieved; more than 20 seconds warning is achieved for necessary TA's, while many unnecessary TA's (55 percent) are eliminated.

One additional note: a low level jet fighter closing at 360 kts would be afforded 32 seconds warning time providing 10 extra seconds for visual acquisition.

### 6.3.2 Traffic Advisory Logic Optimization - the Altitude Test.

Returning to figure 13, attention is turned to the relative altitudes of TOP at CPA.

The S-76 flew commercial helicopter routes, sometimes overflying airports or underflying approach corridors. In reviewing figure 13 it becomes evident that two "modes" exist in the relative altitude spacing. Traffic is clustered from 0 feet to approximately 450 feet relative altitude. This natural clustering suggests an altitude filter for TA logic.

An appropriate altitude filter may be 800 feet because VFR separated traffic reporting altitude would be screened.

It seems prudent, however, to retain the +1200-foot relative altitude window used by TCAS II for screening of proximity traffic.

Aircraft departing airports or helipads present a possible hazard of climbing into a TCAS I aircraft using only a simple altitude filter. To protect against these intruders, TCAS II uses a vertical tau threshold, which computes the time to closest approach in the vertical plane. More details about a vertical tau threshold are contained in section 7.1.2.



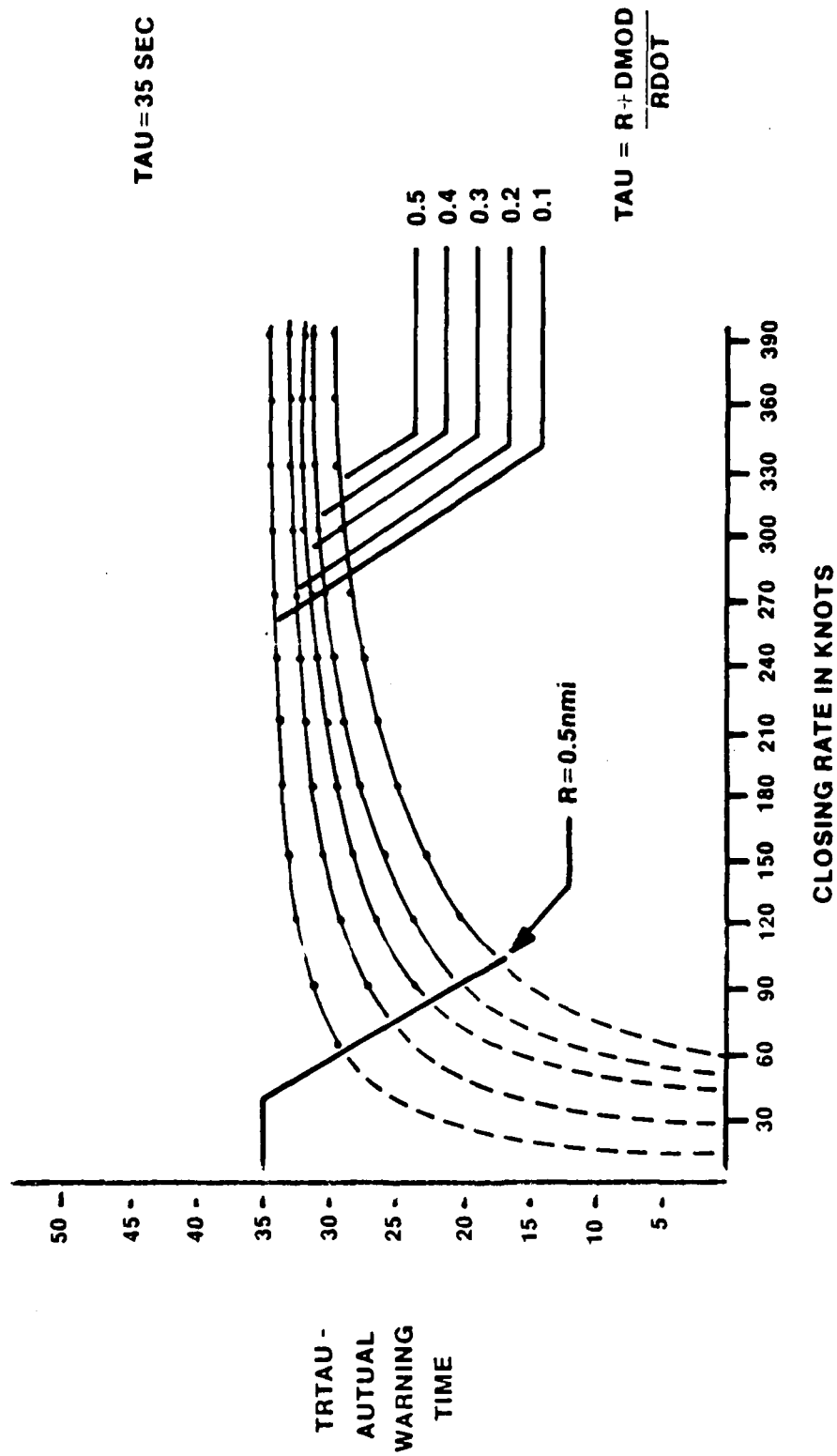


FIGURE 17. ACTUAL WARNING TIME WHEN TAU=35 SEC FOR VARYING DMOD AND THREAT CLOSURE RATES

### 6.3.3 False Track TA Rejection.

Aircraft tracks which receive fewer than 10 updates before deletion are considered false tracks (after TCAS II data analysis). Of the data base from the S-76 flights, approximately 60 percent of all TA eligible tracks fall into this category.

To find methods to reduce the false track rate, it is necessary to examine the characteristics of these tracks. Figures 18 and 19 show closing rates and typical update counts before track deletion.

Figure 18 shows that 58 percent of all tracks have closing rates at or below 500 knots. Similarly, 70 percent of all tracks closed at 600 kts or less. These tracks are pesky because while they don't last long, they immediately qualify for TA status by virtue of their high speeds. Even though they die out rather quickly, they constitute a distraction to the pilot. In section 5 (surveillance), a recommendation was made to limit the maximum tracked rate to 600 kts. Applied to this TA analysis, the limit reduces the TA rate in this data base by approximately 30 percent.

Figure 12 shows a result discovered in past TCAS II TA analysis: tracks formed on fruit very often do not last more than three scans. This lifetime includes three scans to form the track and five scans coast period. TCAS I can take advantage of this result by applying a simple track establishment criterion: tracks cannot be eligible for TA status until four valid reports are received. There is, however, a potential for a penalty of reduced warning time in the interference limited case (see section 5), when scan periods are increased. To assuage this deficiency, an enhancement to the track establishment criteria would make use of the defruiting bit developed in section 5. Any tracks formed on target reports rather than simple replies would be immediately eligible for TA status. The defruiting bit would be carried as part of the ITF and would be a suitable indicator flag.

The MOPS requires tracking nonaltitude reporting aircraft (all Mode C code bits equal zero) versus tracking aircraft with illegal codes. Reference 3 established that this is an effective technique in reducing false tracks and their associated TA's.

To further reduce false tracks, a bearing filter was employed. Correlation windows of 30° were applied initially and found to be an appropriate size. The experiment indicated some gain in using a bearing filter to reduce tracks formed on false, but only a success rate of approximately 50 percent in reducing false tracks. This success rate is obtained through random chance.

6.3.4 Multipath TA Rejection. In the low altitude flight regime of helicopters, the problem of multipath was expected to be severe. One incident was reported by a Technical Center pilot where multipath from the Potomac River was displayed as a second target. The position of the multipath target coincided with the reported position of a second real aircraft by ATC, resulting in confusion over the correct position of the second real aircraft.

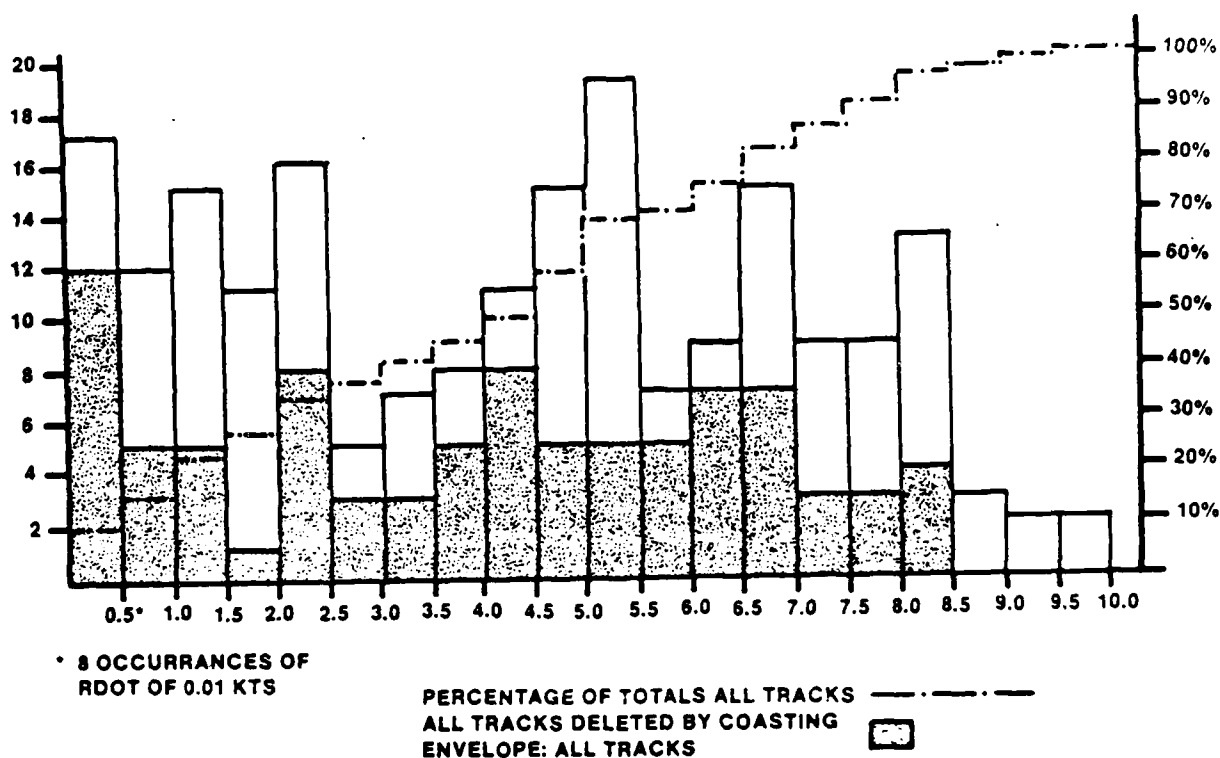


FIGURE 18. HISTOGRAM OF CLOSING RATES OF FALSE TA'S

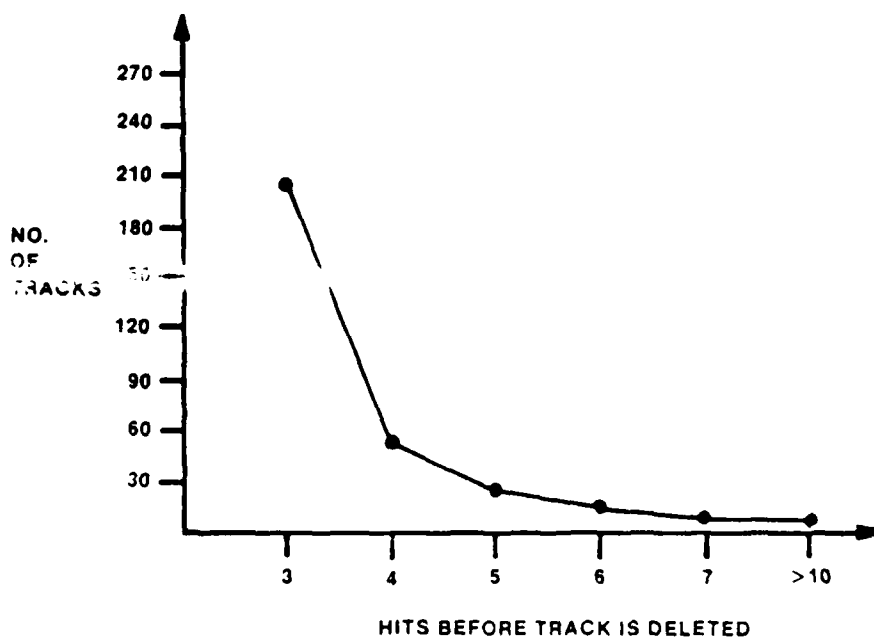


FIGURE 19. NUMBER OF UPDATES DURING FALSE TRACK LIFE

When the data from the Potomac incident was examined, the reason for the strong image was clear. Nearly all of the correlating replies were received on the bottom antenna. Bottom antenna susceptibility to multipath is well documented, and two techniques have been developed for TCAS II to combat it. One technique marks a multipath track based on encounter geometry and renders the track ineligible for TA status, which is done in surveillance (reference 15). The other technique disallows a track to enter TA status until established (see 6.3.3).

These two techniques work together; the geometric technique marks a track before it becomes established; the establishment technique recognizes a track as multipath and does not display it.

One drawback to the geometric technique is the requirement to know actual height above terrain (i.e., radar altitude). Many helicopters do not have radar altimeters, but a fair percentage, such as corporate and offshore, do have them. This report, therefore, recommends that an enhanced TCAS have provision to sense the direct current level proportional to altitude and status (per ARINC standard) that are supplied. When radar altitude is not available, barometric altitude should be used to determine height above terrain. The use of barometric altitude was suggested by MIT Lincoln Laboratory, and found to work well when applied to the Technical Center data base.

6.3.5 Aircraft on Ground. Aircraft on the surface with operating transponders can cause numerous TA's and display saturation, which one FAA pilot called "overwhelming." The impetus is strong to eliminate this source of interference.

The FAA test pilots could regularly identify aircraft on the ground by their altitude tags, but only after being distracted by the TA. Even after an aircraft was dismissed as causing no threat, the display symbol was still present causing clutter and distraction by virtue of its color.

MIT Lincoln Laboratory proposed an interesting solution (reference 7) whereby a rough estimate of the ground is made at takeoff in the barometric altitude. Aircraft that satisfied on-ground detection criteria would be displayed "G" and would be classed proximity traffic (not TA eligible).

This idea has merit because it reduces clutter and distraction. It is probably most effective at altitudes of approximately 700 feet above ground level (AGL) or greater.

The optimum solution would be the use of radar altitude to determine the actual height above ground. A fair portion of aircraft that operate in terminal areas, corporate and commercial, report equipment with radar altimeters (reference 5). This report, therefore, recommends an option to TCAS I, for a radar altimeter input.

The Technical Center experimented with ground bounce of TCAS interrogations and replies to find actual altitude. As with all good multipath, the interrogator's reflections were easily visible in the transponders intermediate frequency (IF) output. When the transponder antenna was oriented toward the reflecting surface, the level of the reflected interrogations was approximately -50 decibels relative to one milliwatt (dBm). The reverse path was approximately equal; transponder replies were detectable at the TCAS I. This technique has two

obvious limitations, however. It becomes ineffective below approximately 300 feet, and produces excessive reflections from buildings. This second limitation could be assuaged by a directional antenna with added cost.

Given that actual height above ground can be determined, it is necessary to determine the optimum altitude buffer for screening aircraft on the surface. The buffer size should be large, to capture altitude encoder variations, but small so that aircraft leaving the ground will afford timely protection.

Altitudes of surface aircraft were logged while the S-76 sat on the ground in Philadelphia, New York, and Washington. The distribution (one sigma) of relative Mode C altitudes ranged from +13 to -113 feet (barometric). This distribution leads to a buffer which can be built around the ground estimate. To encompass the data range plus a small margin, a buffer size of 150 feet (concordant with TCAS II) is recommended by this report. Thus, the on-ground parameter becomes:

$$\begin{aligned} Z_{\text{buff}} &= Z_{\text{ground}} + 150 \text{ feet} \\ Z_{\text{buff}} &= (Z_{\text{baro}} - Z_{\text{radar}}) + 150 \text{ feet} \end{aligned}$$

Aircraft whose reported altitude is less than  $Z_{\text{buff}}$  should be tracked by surveillance but not be eligible for display status.

Assuming that an aircraft takes off and climbs out at a rate of 1,000 feet per minute (bin transistors every 6 seconds), this aircraft would be reliably detected as airborne in not more than 12 seconds. At that climb rate, a TCAS equipped helicopter operating at altitudes of 300 feet AGL or less would be afforded virtually no protection in the worst case. Therefore, whenever a helicopter is operating at low altitudes, e.g., 500 feet AGL or less, and is equipped with radar altimetry, it is advisable to adopt Lincoln's approach and display ground targets as proximity level denoted by "G."

6.3.6 Tau Oscillation. Redundent TA's have been observed on tracks whose tau oscillates about the TA threshold. On successive scans tau falls below, then above, the TA threshold due to range rate variations. Each time tau falls below, a new TA is issued with associated aural alerting. A similar condition exists in altitude oscillations.

The need for hysteresis was illuminated by several tracks exhibiting rather large range jumps (see section 7.3.3). In trying to track through the range jumps, the tracker was generating rather large range rate excursions. The computed value of tau was oscillating as a function of the rate excursions. Figure 20 shows an example of tau oscillation.

6.3.7 Optimized Helicopter TA Logic. This section compiles the key features of the TA logic outlined in section 6.

- a. TCAS I velocity filter should be set to 600 knots.
- b. Non-Mode tracks should pass a track establishment criteria, i.e., updated four scans before being eligible for traffic advisory status.

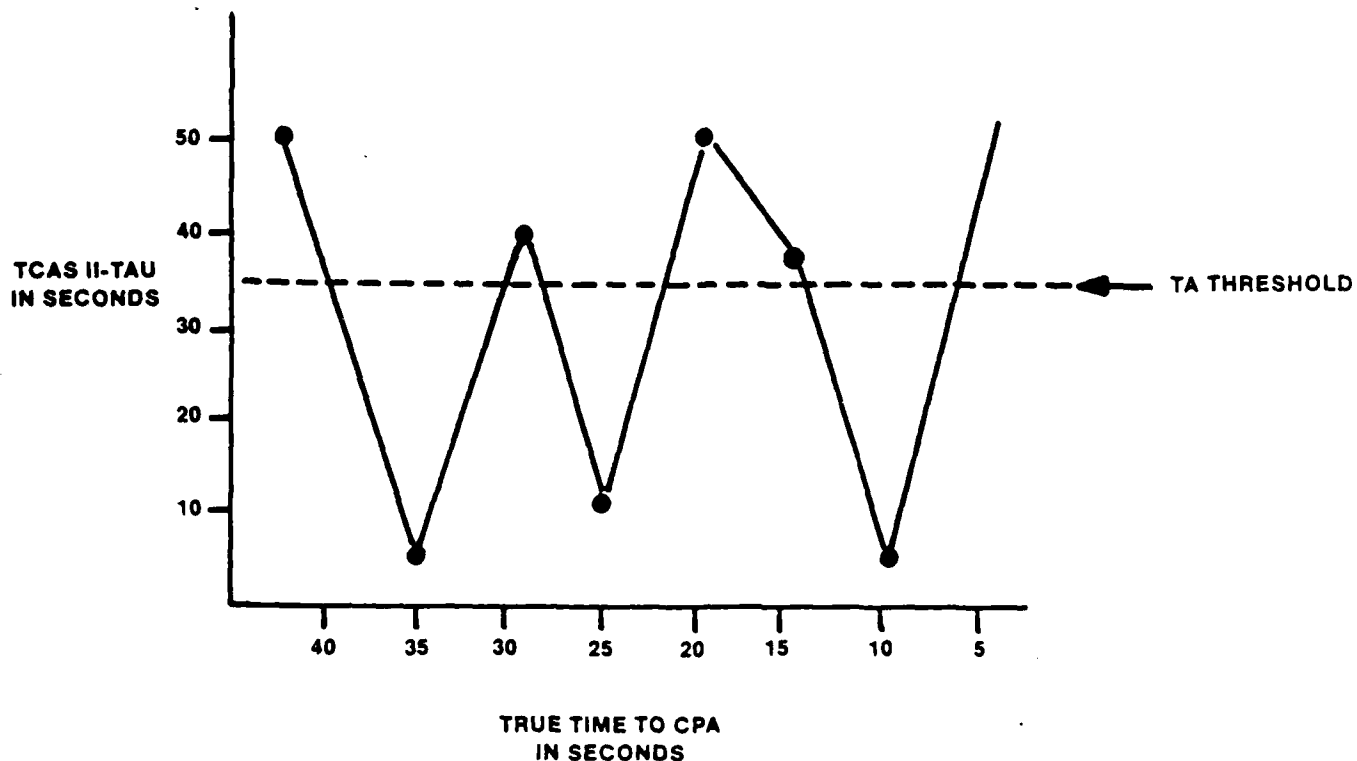


FIGURE 20. EXAMPLE OF OSCILLATING TAU

- c. Tau calculation as in equation 9.
  - d. TCAS I should sense radar altitude as an option.
  - e. When TCAS I equipped helicopters are flying at or below 500 feet (AGL) aircraft on ground should be displayed rather than suppressed, as proximity level denoted as "G."
7. If the aircraft is in the TA range, the TCAS I should display the TA as follows following divergence to prevent redundant TA's from range or rate oscillation.

#### 7. EVALUATION OF AN ENHANCED TCAS I.

This section ties the results of sections 5 and 6 together to verify that the principles contained therein make sense from a system perspective.

## 7.1 TRAFFIC ADVISORY PRESENTATION.

7.1.1 Reduction of Unnecessary Alerts. When the recommendations of section 6 (TA logic optimization) were employed, the rate of unnecessary alerts was reduced approximately four to one. This a substantial reduction considering that the basic philosophy of a tau based threat logic remained unchanged.

When the recommendations of section 5 were employed, i.e., defruitting or discarding illegal mode C replies, the false TA rate in Non-Mode C was reduced approximately eight to one. The end result is that the TA rate is approaching manageable proportions.

7.1.2 Alerts Against Real Aircraft. In section 6.3 a definition was given for necessary alerts versus unnecessary alerts. A necessary alert results when the actual position of a threat aircraft (at CPA) falls within 0.5 nmi and 500 feet altitude of the TCAS aircraft, as predicted by the tau based threat logic.

In this section the accuracy of the predicted positions of the existing TCAS II TA logic versus the optimized TA logic of section 6 are compared.

Of the 12 necessary TA's in the data base, the existing logic alerted against every one with a mean warning time of 33 seconds. All TA's except one provided 25 seconds or more of warning time. A single TA on an accelerating intruder provided 14 seconds warning time.

Using the optimized TA logic, the mean warning time was 22 seconds. All TA's except two provided at least 18 seconds warning time. One of the TA's provided 16 seconds warning time. This is the same TA that provided 14 seconds using the TCAS II logic. The other TA yielded 7 seconds warning against an aircraft descending into the terminal area. When an altitude tau test was employed, the warning time increased to 27 seconds.

The details of the TAU algorithm include a prediction of time to coaltitude as the quotient of relative altitude and relative altitude rate, and a TAU threshold of 20 seconds (in accordance with 6.3.1).

7.1.3 TA Logic Sensitivity to Range Measurement Noise. In some of the slower closing rate encounters, range jitter caused range rate variations of up to 60 knots. When the error component was subtracted from the true tracked closing rate, the warning time was reduced but never fell below 18 seconds. The 0.5 nmi DMOD combined with slower closing rates kept the warning time above 18 seconds. When the error added to the true closing rate, warning times were increased typically to 28 or 30 seconds.

Range measurement jitter significantly affects only tracks whose closing rates are sufficiently slow such that a DMOD based TA affords sufficient warning.

7.1.4 TA Logic Sensitivity to Accelerating Intruders. One TA from the data base resulted in 16 seconds warning time. This aircraft was closing very slowly until just outside DMOD and then began to converge rapidly. Both TCAS II and optimized TCAS I failed to provide at least 20 seconds warning.

The case of the accelerating intruder illuminated a potential problem area. To study it further, the optimized TA logic was then subjected to encounters at various rates and from several turning radii in computer simulation. Curvilinear flightpaths were modeled for both TCAS and the intruder to produce an accelerating closing rate profile. The resulting warning times were not less than 16 seconds for collision courses, and warning times as low as 3 seconds for horizontal miss geometries. Figure 21 summarizes the results of the simulation.

Figure 21 shows a minimum warning time of 16 seconds for an intruder turning maneuver of 5° per second. Considering a more realistic 3° per second turn, the minimum warning time produced in simulation was 17 seconds (the 3°/second case is not shown in figure 21). TCAS II produced a minimum warning of 28 seconds for collision courses and 12 seconds for a horizontal miss of 0.5 nmi.

7.1.5 TA Rates. In this section, alert rates for a minimum TCAS I are compared to the optimized TCAS I and also compared to TCAS II (version 9.0).

In Boston, Atlantic City, and in the New York area the advisory rates were approximately equal. Minimum TCAS I exhibited proximity level alerts at a rate of about 100 per hour. TCAS II generated approximately 32 caution level alerts (TA's) per hour, and optimized TCAS I generated 4 TA's per hour. In Washington, the rate was slightly less, averaging 80 proximity level alerts (minimum TCAS I), 25 TA's (TCAS II), and 3 TA's (optimized TCAS I) per hour.

The highest rates were observed in Philadelphia, due to a proliferation of Non-Mode C targets. Those rates were 110 per hour (minimum TCAS I), 40 per hour (TCAS II), and 5 per hour (optimized TCAS I).

Alert reduction in Boston, Atlantic City, and New York was primarily due to the change in the tau calculation. A lesser effect was due to the track establishment criterion of four scans compared to three used in TCAS II. In Washington, the primary reduction was due to multipath reduction and aircraft on-ground detection.

In Philadelphia, the two primary vehicles for TA reduction were the four-scan track establishment, and the 600-kt limit imposed on closing speeds. These two combined to eliminate many non-Mode C tracks formed on fruit that would have created TA's.

## 7.2 MULTIPATH REJECTION.

The Washington, D.C., flight data base was reviewed for the occurrence of multipath. These data were chosen because the Washington flight log contains the most notes regarding multipath TA's.

The data base contains 1 hour and 40 minutes of flight data. A total of 28 multipath tracks were picked out. The track characteristics are shown in table 9.



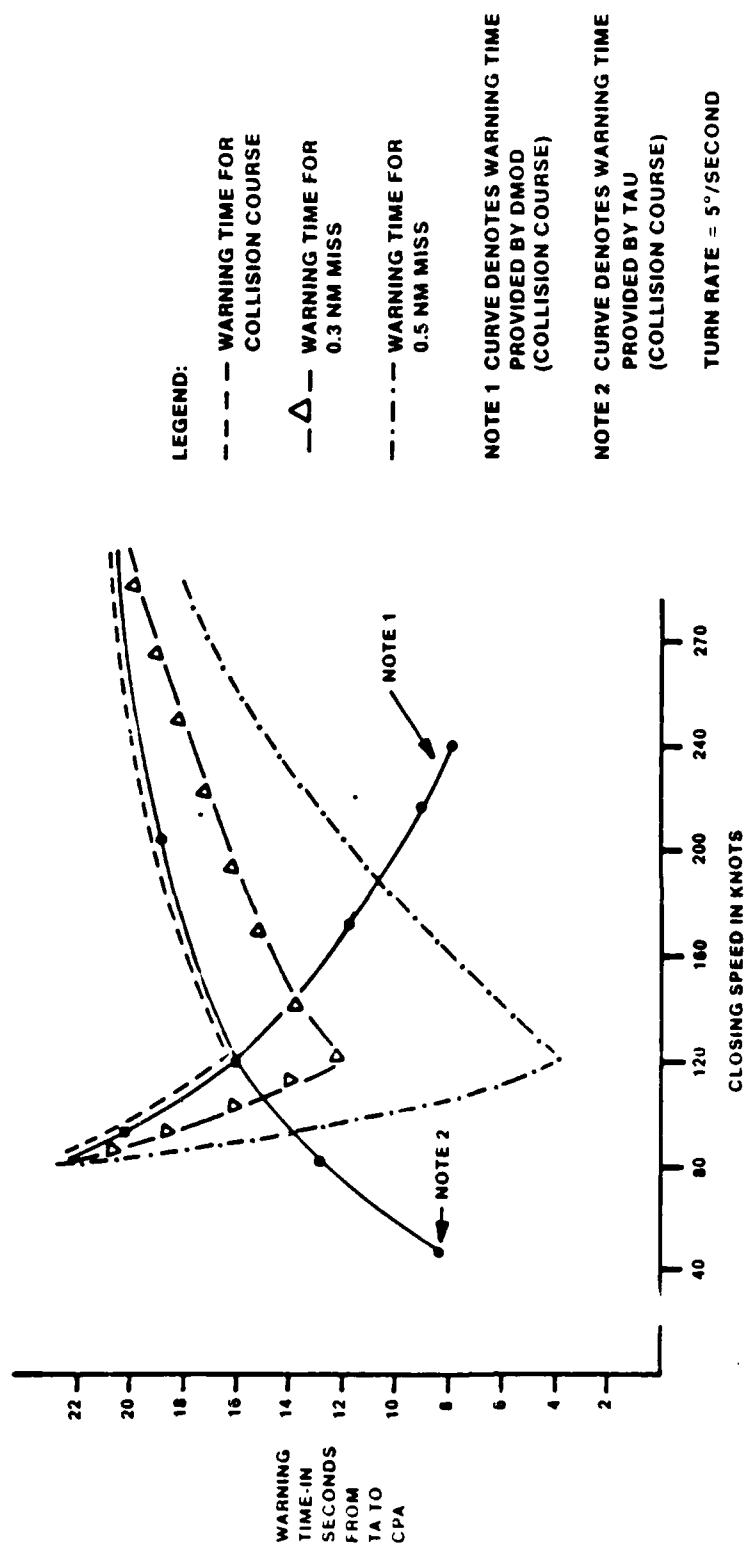


FIGURE 21. WARNING TIME OF OPTIMIZED TA LOGIC (TCAS I) VERSUS CLOSING RATE AND MISS DISTANCE

TABLE 9. TYPE AND DURATION OF MULTIPATH TRACKS  
FROM THE WASHINGTON, D.C., FLIGHT DATA

<u>Quantity</u>	<u>Type</u>	<u>Duration</u>
11+	Mode C	1 Scan
3+	Mode C	2 Scans
2+	Mode C	3 Scans
10+	Mode C	5 or more scans
2+	Non-Mode C	10 Scans
28	Total Tracks	

The non-Mode C tracks in table 9 were the result of corrupted Mode C replies; they will not be displayed if TCAS I tracks only NAR replies. This is a correct result.

Of the 28 total tracks, none would have been eligible for display status considering the smaller altitude window and track establishment criteria proposed in section 6. Under the existing TCAS II logic (implemented in the S-76), three tracks would have been eligible for display status. Two of those tracks would have been displayed 20 seconds each, and one of these prompted pilot comments when the S-76 pilot observed it.

The quantity of these multipath tracks would have been reduced if a working radar altimeter input was provided. This became evident when the data base was subjected to the geometric algorithms proposed by MIT. Once the barometric altitudes were corrected to reflect actual height above ground, the performance of the algorithm was markedly improved. In fact, only three multipath tracks would have progressed to the track establishment stage. None would be eligible for display.

### 7.3 TRACKER ANOMOLIES.

This section describes several track anomalies which are likely to be peculiar to the TEU or the S-76 installation.

7.3.1 Close Range Zero Rate Tracks. In screening the flight data base for TA eligible tracks, a particular class of tracks emerged. In all cases, their range to ownship was 100 nm. Since the range was 0, these tracks were updated six or so times before coasting out.

In the Washington data base alone, 13 of these tracks were found. The replies which formed and extended these tracks were examined, and the following characteristics were noted:

- a. The replies always contained illegal Mode C codes.
- b. The replies always appeared in the bottom antenna WS sequence, never on the top antenna. Also, the replies are distributed over several WS levels.

c. The range of the replies always remained the same (0.18 nmi), regardless of helicopter altitude.

d. The replies always occurred in pairs spaced 0.01 nmi.

The initial impression was that these tracks were the result of ground backscatter of replies or interrogations. However, the independence of tracked range on helicopter altitude rules out reflected replies (or interrogations) as a source of the tracks.

A more likely cause is spurious transponder output at the end of the mutual suppression pulse. Lincoln incorporated an option in the TEU to select either a long (200 microsecond) suppression or a short (30 microsecond) suppression pulse. The S-76 TEU incorporated the short pulse. Considering that the total duration of the interrogation is 27.5 microseconds, the delay imposed by the difference (30-27.5 microseconds) equates to 0.19 nmi in free space.

Two solutions to this anomaly are: a slightly longer mutual suppression pulse (60 microseconds) and diminished power on the bottom antenna. These solutions were effective in TCAS II.

7.3.2 Extreme Negative Altitude Tracks. Occasionally, tracks formed distinguished by tracked altitudes of -800, -1000, or -1200 feet, with a propensity toward -1000 feet. While it is possible that a nearby aircraft is remitting bad Mode C codes, it is more likely that fruit replies were being corrupted. The altitudes -800, -1,000 and -1,200 are unique in that each altitude requires only a single code bit set; the rest remain zero. These are the only altitudes in the Gilliam Code with this characteristic.

Incidence of these tracks rose sharply in the airport traffic area where density increased. Evidently, fruit pulses aligned to form brackets or NAR replies caused bracket detection, and a singular code pulse was declared in the "C" bit positions. These tracks always formed, then coasted out immediately. The random nature of range and range rate at track formation, combined with their short lifetimes, give strong evidence that these are fruit generated tracks.

The origin of these tracks was most probably in the TEU reply processors. It is possible that dynamic minimum threshold level (DMTL) gating was clipping altitude code pulses in replies from aircraft on the ground; alternately, it is possible that chance combinations of pulses were forming replies. In any event, due to the fairly low frequency of occurrence, no action is necessary, beyond the identification of these tracks to eliminate them.

7.3.3 Range Jumps. Occasionally, tracks formed on fruit indicated by short lifetimes and unrealistically high range rates. Several tracks in particular closed to zero range and should have progressed smoothly through "CPA" and continued outbound, but, instead, made a discontinuous jump to a range beyond 10 nmi (note that surveillance was range gated at 6.0 nmi). On the following scan, the track discontinuously jumped to a range around 0.25 nmi. On subsequent scans the range of these tracks alternated between 0.25 nmi (or so), and 10.5 nmi (or so). Total life times lasted between 10 and 15 scans.

Each time one of these tracks oscillated toward zero range, a new TA was generated (with associated aural alert).

This condition has its origins in Lincoln's surveillance subsystem and a simple software change will correct it. However, a very important condition, tau oscillation, was illuminated by these occurrences. In section 6 a recommendation was made to require hysteresis on TA eligible tracks. Hysteresis would have eliminated the redundant TA's on these tracks, as well as redundant TA's on aircraft just skimming the edge of the protection volume.

7.3.4 Range Offset. When examining the data base for multipath tracks, a condition previously reported by MIT was noted. Several tracks thought to be multipath, i.e., outrange and equal altitude with a prominent track, were actually duplicate tracks offset from the real track by 0.1 nmi. The offset was constant regardless of the range of the real track.

This offset track phenomenon resembles the "late Mode C" effect, characteristic of directional (sector) interrogation TCAS. Late Mode C occurs when victim transponders answer interrogations comprised of P<sub>2</sub>, P<sub>4</sub> pulses rather than P<sub>1</sub>, P<sub>3</sub> pulses. However, the TEU: (a) did not transmit either P<sub>2</sub> or P<sub>4</sub>, and (b) late Mode C offsets are 0.16 nmi rather than 0.10 nmi. More likely, the offset tracks in the S-76 data base are the result of the double pulse suppression pair in the TEU interrogations. In Technical Center laboratory tests, victim transponders were 20 to 30 percent more likely to answer interrogations with double pulse than single suppression. A side effect of the double pulse suppression, however, is a small amount of range jitter, which is believed to cause the S-76 range offset.

Technical Center engineers, therefore, concur with the MIT report in attributing the range offset to the double suppression WS. No action is necessary because the TCAS I MOPS specifies a single pulse suppression scheme.

7.3.5 Track Merge. One feature of the TEU surveillance is the elimination of redundant tracks by merging those tracks with similar range and altitude characteristics. Occasionally, tracks were merged when they shouldn't have been. Figure 22 shows an interesting example of an incorrect merge. Tracks 19 and 23 were two tracks distinct in range, altitude, and AOA.

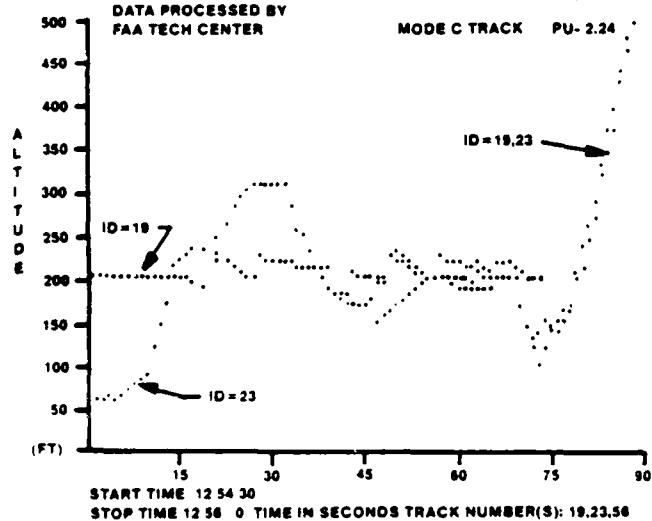
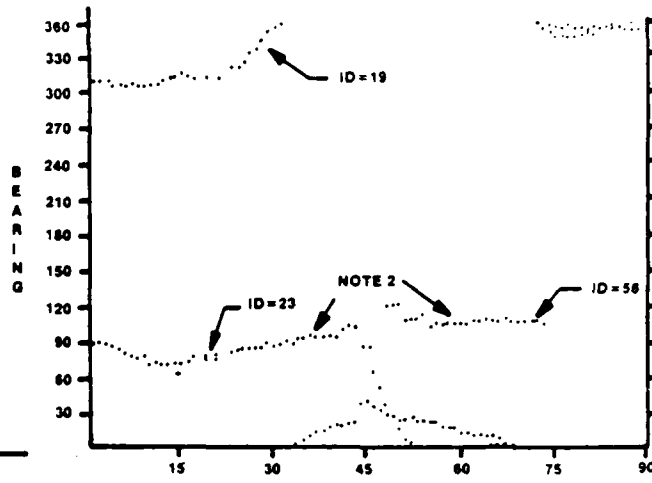
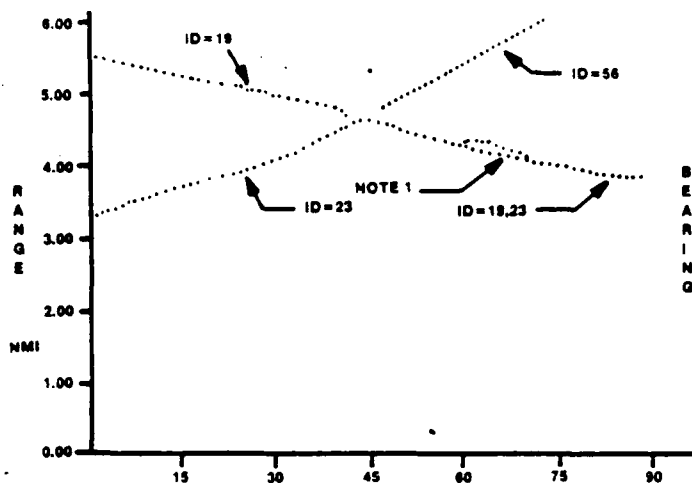
They crossed at approximately 45 seconds and were merged. Track 56 was then formed and continued outbound. Track 19 continued inbound, a correct result, but surveillance assigned track number 23 in addition to track number 19 to the reply stream. Eventually, two TA's were generated on track number 23, because surveillance had two track numbers assigned. It is quite evident in figure 22 where the tracks were merged.

To prevent this condition it may be useful to employ range rate in the track merge logic. TCAS II uses rate differences of 40 kts as a parameter in its merge logic. TCAS II also uses an altitude rate of 600 feet per minute as an altitude parameter. These parameters seem reasonable for adoption into TCAS I.

## 8. SUMMARY OF RESULTS

### 8.1 PILOT EXPERIENCE

Six FAA Technical Center pilots flew the TCAS equipped S-76. Their evaluation highlighted two points: (a) TCAS is invaluable in augmenting the pilot's ability



- NOTES:
1. THE REMAINING TRACK CARRIED TWO IDS. UNTIL EXHAUSTION
  2. THIS BEARING TRACK IS FOR ONE AIRCRAFT EVEN THOUGH THE TRACK ID WAS CHANGED

FIGURE 12 - TRACK IDENTIFICATION AND TRACK NUMBER ASSIGNMENT  
INTO ONE

to see and avoid, and (b) unnecessary workload is a serious detractor to flight safety. Additional responses indicate that the display configuration is useful, but that false traffic advisories and advisories against intruders on-ground are a nuisance and contribute to workload.

## 8.2 TCAS SURVEILLANCE.

In order to provide adequate warning time against real threats and minimize false advisories, two schemes were explored. The first is the expansion of the surveillance volume from 4.0 miles radius to 5.0 miles radius, and the second is a reduction, from three to two, in the number of replies to initiate a track. The expansion of the protection volume proved reasonable especially under interference limiting. However, the new track initiation, while feasible, did not result in a significant benefit over the existing three-reply criteria. This result is due to the requirement that at least two replies are received, via WS, in every interrogation scan.

## 8.3 TCAS TA LOGIC.

In section 7, the existing TCAS II TA logic was modified to be better suited to TCAS I. The optimized logic provides a 20-second warning time against low speed intruders and up to 30 seconds warning against higher speed intruders. Additionally, features were proposed to limit the frequency of false and nuisance alerts. The optimized TA logic was then tested against a live flight data base, and the results were compared to TCAS II logic performance with the same data base. In linear encounters the optimized TA's logic attained the designed goal of 20 seconds minimum alerting, while reducing nuisance TA by approximately eight to one. Against accelerating intruders the optimized TA logic was somewhat worse than TCAS II, on the average, affording as low as 17 seconds warning for standard rate turns compared to 28 seconds for TCAS II.

## 9. CONCLUSIONS.

1. Federal Aviation Administration (FAA) Technical Center pilots favorably rated Traffic Alert and Collision Avoidance System (TCAS) but emphasized that false and nuisance Traffic Advisories (TA's) are unacceptable.
2. Based on minimum operational performance specifications (MOPS) for TCAS I, adequate TA information can be obtained from existing TCAS I surveillance.
3. The surveillance range can be expanded from 4.0 miles to 5.0 miles to provide more protection from high speed intruders.
4. The use of radar altitude in helicopters so equipped can dramatically improve the performance of multipath and on-ground aircraft TA elimination logic.
5. By comparison, the existing track initiation criteria is approximately as effective as the proposed reduced reply initiation criteria. There is no obvious benefit to changing to the proposed criteria.
6. Several proposals were made in section 7 to improve the ratio of real TA's to false and/or nuisance TA's. Most of these were adapted from TCAS II and proved to be gainful in TCAS I.

#### 10. RECOMMENDATIONS.

1. Traffic Alert and Collision Avoidance System (TCAS) I should, as an option, be capable of sensing radar altitude from helicopters so equipped.
2. The TCAS I surveillance outlined in RTCA SC147-223 should be adhered to in a TCAS I, with the exception that surveillance range should be expanded to 5.0 nautical miles.
3. Whenever possible, installed TCAS I systems should include barometric altitude sensing to provide traffic advisory (threat screening) logic.
4. False and unnecessary alerts can detract from TCAS usefulness by increasing workload. The decision to install a minimum TCAS I (as opposed to an enhanced TCAS I) should be carefully considered.

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## GLOSSARY

AGL	Above Ground Level
ATC	Air Traffic Control
ATCRBS	Air Traffic Control Radar Beacon System
CPA	Closest Point of Approach
dBm	Decibels Relative to 1 Millowatt
DBW	Decibels Relative to 1 Watt
DMOD	Distance Modification; a Traffic Advisory Logic Parameter
DMTL	Dynamic Minimum Threshold Level
EAIR	Extended Area Instrumentation Radar
FAA	Federal Aviation Administration
FRUIT	Replies from Uninterrogated Beacon Transponders
GA	General Aviation
IF	Intermediate Frequency
IFR	Instrument Flight Rules
ITF	Intruder Track File
kts	Knots (Nautical Miles per Hour)
MIT	Massachusetts Institute of Technology
Mode C	Transponder Operating Mode Where Encoded Baro Metric Altitude is Remitted
MOPS	Minimum Operational Performance Specification
m.s.l.	Mean Sea Level
NAR	Nonaltitude Reporting
NMAC	Near Midair Collision
nmi	Nautical Miles
NTSB	National Transportation Safety Board
RDOT	Relative Speed Expressed in Knots
RF	Radio Frequency
TA	Traffic Advisory
TATHR	Traffic Advisory tau Threshold
tau	An Expression of Time Remaining to CPA
TCA	Traffic Control Area
TCAS	Traffic Alert and Collision Avoidance Systems
TEU	TCAS Engineering Unit
TOP	Target of Opportunity
TRTAU	Actual Time to Closest Point of Approach
WS	Whisper Shout

APPENDIX

VERIFICATION OF THE TRACK MODEL IN SECTION 5.1.1

In section 5.1.1, the likelihood of extending a false track for n scans was computed. In this appendix, actual flight data will be compared to the results of the model used in 5.1.1.

A review of the model:

The binomial distribution is used to calculate the cumulative probability of receiving one correlating reply in n scans:

$$P_r \text{ } x \geq c = \sum_{x=c}^n \binom{n}{c} (p)^c (1-p)^{n-c}$$

where c = 1 (one reply to extend track)

n = total scans

p = update rate

1-p = miss rate

P<sub>1</sub> the update rate, is determined from:

$$P = P_{fr} = f_r \times W_s \times R_g \times 12.6 \text{ } \mu\text{sec} \times (W_n + R_g)$$

In this problem:

$$\begin{aligned} W_s &= 22 \\ R_g &= 6 \text{ nmi} \\ W_n &= .250 \end{aligned}$$

The fruit rate is taken from observation of the Washington area traffic on the morning of December 11, 1985. An average of 1.0 non-Mode C tracks were maintained, yielding a fruit rate:

$$\begin{aligned} f_r &= 150 \times 1.0 \left( \frac{r_1}{30} \right)^2 \\ &= 3750 \quad \text{where } r_1 = 6.0 \text{ nmi} \end{aligned}$$

which yields a fruit update rate:

$$\begin{aligned} f_r &= 3750 \times 22 \times 6 \times 12.6 \text{ } \mu\text{sec} \times 0.250 + 6.0 \\ &= 0.259 \\ &= 25.9\% \end{aligned}$$

Using this fruit rate in the binomial distribution the probability of extending a false track N times is:

$$\begin{aligned} P_{te} &= 0.216 \\ P_{te} &= 0.047 \\ P_{te} &= 0.01 \\ P_{te} &= .002 \end{aligned}$$

From the flight data, a summary of 38 false non-Mode C tracks was compiled. The data includes 20 non-Mode C tracks which were not updated, 9 updated once, 3 update twice, etc. From the data base, the following numbers were derived.

$$\begin{aligned} p_{te} &= 9/38 = 0.236 \\ p_{te} &= 3/38 = 0.083 \\ p_{te} &= 3/38 = 0.083 \\ p_{te} &= 1/38 = 0.026 \end{aligned}$$

Table A-1 compares the measured versus computed:

TABLE A-1. MEASURED VERSUS CALCULATED PROBABILITY OF TRACK EXTENSIONS

	<u>Measured</u>	<u>Calculated</u>	<u>Error</u>
Pte1	0.236	0.216	8%
Pte2	0.083	0.047	43%
Pte3	0.083	0.01	87%
Pte4	0.026	0.002	92%

The data in table A-1 was from a 10-minute sample of flight data. TCAS was operating at one scan per second yielding 38 false tracks in 600 seconds, or approximately 1 track every 16 scans. Based on the observed environment, a false track rate is predicted:

fruit update rate =

$$\begin{aligned} f_r &= 3750 \times 22 \times 12.6 \mu\text{sec} \times W_n \div 6.0 \\ W_n &= 0.691 \text{ after 2 scans} \\ W_n &= 0.102 \text{ after 3 scans} \end{aligned}$$

then,

$$\begin{aligned} f_r &= 0.718 \text{ after 2 scans} \\ f_r &= 0.102 \text{ after 3 scans} \end{aligned}$$

$$P_r = \sum_{x=c}^n \frac{n!}{c!(n-c)!} (p)^c (1-p)^{n-c} \times 0.102$$

$$\begin{aligned} P_r &= 0.416 \times 0.106 \\ &= 0.044 \end{aligned}$$

or 1 false track every 22 scans.

Thus, the predicted false track rate is 1 every 22 seconds, while the measured rate is 1 every 16 seconds.